A review of the factors affecting the biodiversity of Constructed Stormwater Management Systems along roads

Bachelor of Science Thesis

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Technical report
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Cover:
An image of a Constructed Stormwater Management System adjacent to a road in New Zealand. Source: (Whittle 2012).

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Abstract

Constructed Stormwater Management Systems (CSMSs) are usually designed to treat urban runoff, but can act as artificial habitats that support relatively diverse aquatic ecosystems. However, in order to manage these systems in an environmentally friendly way, more knowledge of the factors affecting the biodiversity within these CSMSs is required. The aim of this thesis was to deduce the main factors that affect the biodiversity within CSMSs. The report is split into two main sections: the first part consisting of a literature review and the second containing data analysis. Following the literature review, the factors that appeared to have the greatest impact on the biodiversity within CSMSs were: salinity; pond size and shape; vegetation; nitrogen oxide concentrations; noise; and PAHs and heavy metal concentrations. However, it is apparent that nature is a complex system, with many of these factors interlinked and interrelated; therefore, no factors should be neglected. Furthermore, different species have various tolerance and lethal concentration levels for each harmful factor. Following the data analysis, it became clear that pond age and CSMSs substrate type also have a statistically significant effect on the biodiversity within CSMSs. Pond age may form a polynomial relationship, with biodiversity increasing in the short-term, peaking and then decreasing in the long-term when heavy metal accumulations become lethal. Clay (naturally) based ponds seem to support the highest biodiversity, with PEHD bases slightly negatively correlated and concrete bases very negatively correlated with biodiversity. Future design and management of CSMSs should consider the potential aquatic habitats that these systems have to offer, as well as being primarily designed to limit pollution to the wider environment. To increase the regional biodiversity, the design of CSMSs should be personalised, at a family level, to satisfy the different needs of Fish, Amphibians and Invertebrates, and to move away from homogeneity and towards heterogeneity.

Preface

The work on this thesis was carried out at Chalmers University of Technology, Sweden, as part of my year abroad on the Erasmus programme. It was performed for the Department of Civil and Environmental Engineering, at Chalmers, and their associates, the Norwegian Public Road Administration (NPRA). It was completed as a small part of the ambitious project to construct a biodiversity neutral E39 highway, along the Norwegian West coast. This thesis is an initial project towards a bigger project, which aims to produce a combined ecological and hydrological model, to assess the functionality and biodiversity of CSMSs. The report was completed in seven weeks, six of which were spent in Gothenburg and one spent working with our Norwegian colleagues in the NPRA office, in Oslo. The primary focus of the thesis was on the literature review, as there was insufficient time to perform a comprehensive analysis of the existing data.

The thesis is worth 15 ECTS, which is the equivalent of 30 credits at the University of Bristol, my home university in the United Kingdom. It was supervised by Dr Ekaterina Sokolova, a member of staff at the Division of Water Environment Technology, Chalmers.

My sincere thanks go to Ekaterina Sokolova, for all of her help, constructive feedback and guidance. Furthermore, I would like to express my gratitude to Sondre Meland (NPRA) and Ricardo Calveiro (Chalmers University of Technology) for their contribution to my project and assistance with general taxonomy. Lastly, I am very appreciative for the great hospitality given to Ricardo and me, by our Norwegian colleagues, during our brilliant stay in Oslo.

Abbreviations

The following abbreviations appear in this report, in chronological order:

WFD – Water Framework Directive

CSMSs – Constructed Stormwater Management Systems

NORWAT – Nordic Road Water

NPRA – Norwegian Public Roads Administration

BMPs – Best Management Practices

WSUD – Water Sensitive Urban Design

SUDS – Sustainable Urban Drainage Systems

LID – Low Impact Development

PCA – Principal Component Analysis

NaCl – Sodium Chloride

PAHs – Polycyclic Aromatic Hydrocarbons

CMA – Calcium Magnesium Acetate

PEHD – Poly-Ethylene High Density

NO_x – Nitrogen Oxides

Cu – Copper

Zn – Zinc

Pb – Lead

Ni – Nickel

Al – Aluminium

Mn – Manganese

Fe – Iron

AADT – Average Annual Daily Traffic

SDI – Shannon Diversity Index

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1. Introduction

Roads play a pivotal part in the infrastructure of countries; however, their construction can lead to detrimental effects on the surrounding environment, with local ecosystems being heavily affected (Thygesen 2013, Balkenhol and Waits 2009, Trombulak and Frissell 2000). Therefore, as engineers, it is our role to try and minimise these harmful consequences of road building and if possible, eradicate these factors all together. It may even be possible to improve some aspects of the surrounding ecosystems through thorough planning of biodiversity-neutral roads and the implementation of road runoff collection and treatment systems (Thygesen 2013, Le Viol et al. 2009, Brand and Snodgrass 2010, Le Viol et al. 2012).

Loss of naturally occurring ponds has happened at an alarming rate, especially in Northern Europe where they have decreased by 40-90% over the last century (Le Viol et al. 2012). These alterations are mainly a result of anthropogenic land use changes, such as building roads. Alarmingly, ponds are also considered one of the most taxa abundant aquatic habitats, at a regional level (Le Viol et al. 2012).

As a result of this, the European Union set up the Water Framework Directive (WFD) in 2000. Part of the WFD is to "*prevent further deterioration, protect and enhance the environmental status of aquatic systems*." P.283 (Andersen et al. 2004). The WFD was inculcated into Norwegian law in 2007 (Thygesen 2013). The second part of the WFD outlines how water should be used sustainably and how all aquatic systems should have an adequate chemical and ecological quality (Andersen et al. 2004).

Consequently there has been an increase in the number of constructed stormwater management systems (CSMSs) along roads (Scher et al. 2004), in an attempt to improve the water quality of surrounding streams, rivers and lakes. The wider ecological effect of road-related chemical pollution has not been well researched, despite clear evidence that contaminants enter and accumulate in the environment and appear to interact with biota (Coffin 2007). Furthermore, although CSMSs are built to remove these harmful pollutants, they can also act as artificial habitats for aquatic species (Brand and Snodgrass 2010, Moore and Hunt 2012). However, there is limited research into the effectiveness of these CSMSs as ecosystems (Scher et al. 2004), as it is an emerging and evolving area of research (Spellerberg 1998). Furthermore, the effect of different factors on the biodiversity within CSMSs has received little attention (Forman 2003).

Therefore, the purpose of this project is to identify the individual factors which affect the biodiversity within CSMSs the most. Furthermore, this research project is a pre-project to a larger, long-term project, with the ultimate aim of designing a biodiversity neutral E39 highway, in Norway, through the use of modelling. The Coastal Highway E39 has the potential to reduce the travel time between Kristiansand and Trondheim by 7-9 hours (Ellevset 2012); therefore, this should bring large economic benefits to the region (Linneker and Spence 1996, Coffin 2007).

In this project, current literatures on the factors that directly affect the biodiversity within CSMSs were reviewed. Therefore, it is important to note that other important factors such as: roadkill (Coffin 2007, Forman and Alexander 1998, Trombulak and Frissell 2000); land fragmentation and roads acting as a barrier (Forman and Alexander 1998, Spellerberg 1998, Coffin 2007); dust (Coffin 2007, Trombulak and Frissell 2000, Spellerberg 1998, Forman 2003); surrounding land use type (Scheffers and Paszkowski 2013, Scher and Thièry 2005); pathways for invasive species (Joly et al. 2011, Spellerberg 1998, Trombulak and Frissell 2000); and, artificial light (Spellerberg 1998), were not reviewed as they tend to affect the regional biodiversity as opposed to the localised biodiversity within CSMSs. Further evaluation of two factors, CSMSs age and substrate type, is also carried out using existing data. The paper concludes by highlighting what are perceived to be the most important factors affecting the biodiversity of CSMSs along roadsides, based on the author’s interpretation of the original reports and data analysis.

2. Aim and Objectives

The aim of this research paper is to deduce the main factors affecting the biodiversity in CSMSs along roads. The findings could then be used to assist in the eventual modelling process used to combine hydrological and ecological modelling, as part of the biodiversity-neutral E39 highway construction project. In order to achieve this aim, the following objectives shall be answered in this report:

- What are the main factors that affect biodiversity in CSMSs?
- Identify two factors that have received little attention in the literature, but seem important, and deduce if they significantly affect the biodiversity within CSMSs, using the available data.

The second objective shall be achieved by analysing the existing data on flora and fauna, which has been collected within the research and development program Nordic Road Water (NORWAT), by Helene Thygesen (2013), as part of her master thesis for the Norwegian Public Roads Administration (NPRA) (Vegvesen 2012).

3. Background Information

This section shall provide some further information on key aspects of this research paper.

3.1. Biodiversity

Biodiversity is the variation of animal and plant life around the world or within a particular habitat (Maclaurin 2008). Furthermore, it consists of all the various organisms and how they interact with each other and is a crucial element within all biological systems (Thygesen 2013). Measuring biodiversity is a monumental challenge because it is ultimately a multidimensional concept; therefore, it cannot realistically be reduced to a solitary number. Instead, there are many different measurements of biodiversity, which simply put can be split into three quantifiable facets: number, which indicates the species richness; evenness, which is the extent numbers of individuals are spread evenly between species; and difference between the species (Purvis and Hector 2000). According to Thygesen (2013), there are five main categories of factors which affect biodiversity. These are: competition, predation, whether species have an active or passive dispersal, abiotic, and biotic factors. This report focuses on the latter two families of factors because the others are natural phenomena which cannot easily be changed by human influence.

Biodiversity loss is one of the greatest modern day challenges, and it is currently happening at an alarming rate (Purvis and Hector 2000). The severity of biodiversity loss can be highlighted by comparing it to other planetary boundaries. The concept of 'planetary boundaries' defines the safe functional space for humanity in respect to the Earth's systems (Rockström 2009). The loss of biodiversity is the worst performing of the nine proposed planetary boundaries, with a current rate of extinction of species estimated to be around 100 to 1,000 times greater than the natural rate. The current rate of extinction of species in the Anthropocene is greater than 100 (number of species per million species per year), when the proposed boundary level is just 10 and the pre-industrial value was only 0.1-1. The Earth cannot sustain these current loss rates without substantial erosion of ecosystem resilience. The most significant factor causing this large increase in extinction rate is changes in land use (Rockström 2009).

In this paper, the biodiversity which is contained within the CSMSs is explored and evaluated. Therefore, the focus is mainly on Amphibians, Invertebrates, Fish and Plant species. Other life forms, such as Birds and Mammals, were mostly neglected as they do not tend to use CSMSs as their primary habitat.

3.2. Constructed Stormwater Management Systems

In this report, CSMSs refer to all of the purpose built systems that control and manage stormwater and urban run-off along roads, unless specifically stated otherwise. According to Hvitved-Jacobsen et al. (2010) the ten structural best management practices[1] (BMPs) for treating and managing highway and urban runoff are: Extended Detention Basins; Wet Ponds; Constructed Wetlands; Infiltration Trenches; Infiltration Basins; Filters; Water Quality Inlets; Swales; Filter Strips, Bioretention and Biofiltration Systems, and Rain Gardens; Porous Pavements. These BMPs try to replicate the predevelopment hydrology of urban sites and try to minimise and reduce the stormwater and urban runoff pollution to the surrounding environment (Hvitved-Jacobsen 2010). Wet ponds are the CSMSs which will be

[1] BMPs can be referred to as different things around the world. Sustainable urban stormwater management in Australia is called Water Sensitive Urban Design (WSUD). Whereas in Europe a similar concept is Sustainable Urban Drainage Systems (SUDS) and in the US is Low Impact Development (LID) (Kazemi et al. 2011).

predominantly used along the E39 highway and so they will receive the primary attention in this paper. Furthermore, the data used in the analysis (see section 6) is taken from nine wet ponds within the Oslo region (Thygesen 2013). A brief description of the relevant structural BMPs, discussed in this paper, are outlined below.

3.2.1. Extended Detention Basins

This BMP does not always contain water between storm runoff events and therefore is sometimes referred to as a dry pond. Its primary purpose is to temporarily store water during storms, to reduce the peak flow rates and to protect facilities located downstream, i.e. it restricts outlet discharges. Settlement of suspended particulate materials may, to some extent, take place (Hvitved-Jacobsen 2010).

3.2.2. Wet Ponds

Unlike the extended detention basins, wet ponds act as shallow lakes containing permanent bodies of water. They consist of a slam basin, which acts as a temporary storage volume, and a main basin, which forms the permanent pool. The slam basin usually needs to be emptied more regularly than the main basin, because of the large size of the heavy metal particles that settle there in comparison to its small basin size (Thygesen 2013). Sometimes the ponds can contain multiple slam basins with different roles, for example one to deal with agricultural runoff and the other slam basin to deal with urban runoff (Thygesen 2013). The ponds act as BMP for the removal of particulate and some soluble pollutants because of their sufficient residence time (Hvitved-Jacobsen 2010). Figure 1 below provides a schematic of how these ponds function, the forebay is representative of the slam basin with the micropool being the main basin.

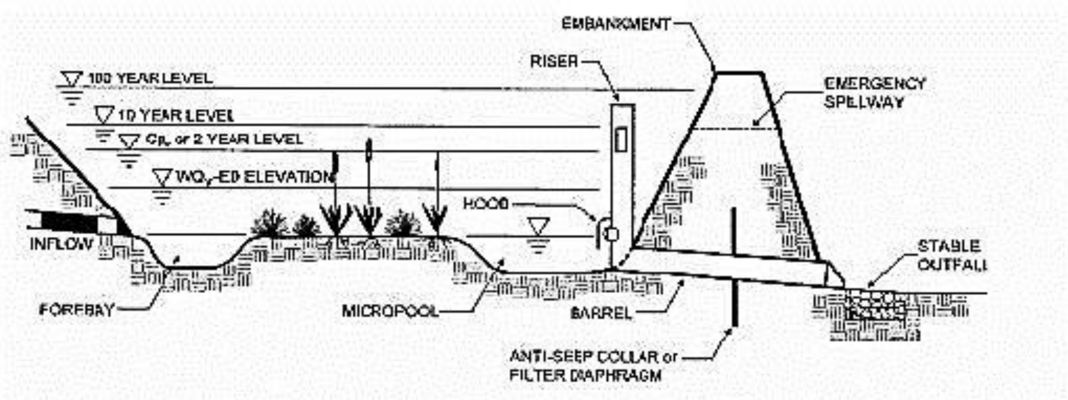

Figure 1: A cross-sectional diagram (not to scale) portraying the functionality of a wet pond (EPA 2012).

3.2.3. *Constructed Wetlands*

These are categorised as densely vegetated areas with shallow water levels of around 0.1-0.3m. They are very diverse with a variable water table and a plethora of different designs and vegetation types (Hvitved-Jacobsen 2010).

3.2.4. *Infiltration Trenches*

Originally, infiltration trenches consisted of holes cased in a filter fabric and then backfilled with aggregates to produce an underground basin. However, modern infiltration trenches are produced by piling up plastic boxes instead. The water entering these trenches either exfiltrates to the adjacent soil or is transferred to an outflow facility (Hvitved-Jacobsen 2010).

3.2.5. *Infiltration Basins*

Water infiltrates to the soil beneath the basin and they are usually designed for first flush volume only. They can also be named infiltration ponds and act as temporary runoff water reservoirs (Hvitved-Jacobsen 2010).

3.2.6. *Swales*

Shallow channels containing flora and used to transport stormwater are defined as swales (Hvitved-Jacobsen 2010). One particular type of swale is a bioretention swale. Bioretention swales collect stormwater, whilst sieving it through a semi-permeable soil media, and then transport the water to a storage facility for reuse or releasing it to downstream drainage systems or other waters (Kazemi et al. 2011). Figure 2, on the next page, provides a visual representation of a bioretention swale.

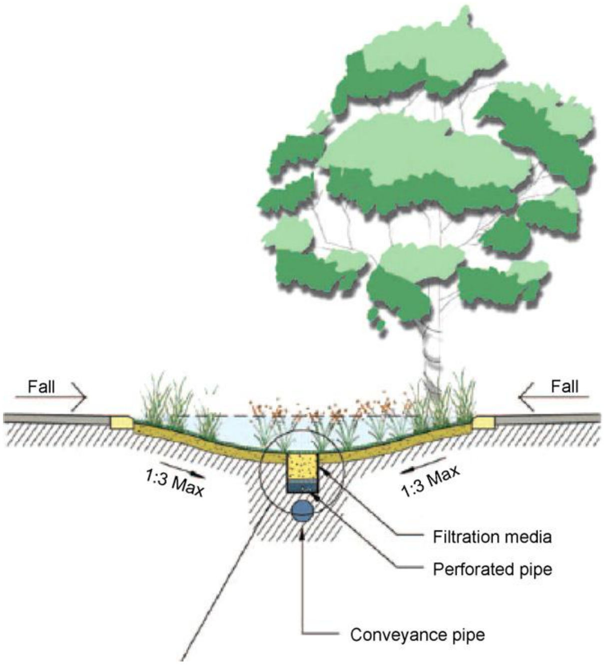

Figure 2: A cross section of a standard bioretention swale, in Australia (Kazemi et al. 2011).

4. Methodology

This section outlines the methods used to produce this paper.

4.1. Overview

To achieve the objectives outlined above (section 2), an initial literature review was first carried out. The literature review focused on the effects that roads have on the biodiversity within CSMSs. Furthermore, case studies of previous biodiversity-neutral road projects and initiatives, centred on CSMSs, were explored. The literature review was conducted continuously throughout the research project, with detailed search words researched as the report progressed and as some factors were identified as more important than others. Additionally, it concentrated on both reports of original investigations and reviews. The literature which was reviewed was all written in English, with the majority of references coming from databases, for example Scopus (Spellerberg 1998).

The XLSTAT statistical analysis add-in for Microsoft Excel was used for the data analyses. It allowed Principal Component Analysis (PCA) to be performed, as well as linear regression and univariate analyses. These analytical techniques and explanations for their use are described in greater detail later in the report (see section 6.1.).

4.2. Limitations

The major limitation of this research project was time. With only seven weeks to complete the report, all of the relevant literature to support any findings had to be found during this short timescale. To manage this challenging lack of time, a detailed project and time plan were constructed at the beginning of the project to aid with time management and minimise the risk of deadline overruns. It is because of this time constraint that only basic, as opposed to more detailed, data analyses were carried out.

Another limitation of this research project is the subjective nature of some of the literature reviewed. According to Spellerberg (1998), some of the reviews he read appeared not objective. For example, some authors decided roads are 'bad' and therefore continued their review in that mind-set.

A final limitation, related to the data analyses, was the reliance on effective and accurate data collection by Helene Thygesen (2013). However, the methods used to collect the data for her Master thesis all seem reasonable and in-line with other methods outlined in the literature.

4.3. De-limitations

This report focuses solely on the factors directly associated with the biodiversity in CSMSs. This is because of the fixed research project deadline and the short amount of time in which to complete the paper. Therefore, as stated in the introduction (see section 1), other important factors affecting the regional biodiversity have not been considered. Therefore, the groups of organisms which are mainly focused on are: Amphibians, Invertebrates, Plant and Fish species. However, the factors that affect the regional biodiversity should also be evaluated during the design and planning stage of any future road construction project, even if not considered for the design and planning of CSMSs along roadsides.

5. Review of factors affecting biodiversity in CSMSs

This segment provides an overview of the factors that affect biodiversity within CSMSs. According to Spellerberg (1998), the ecological effects of roads can be viewed in three different time frames: 'Effects during construction', 'Short term effects (of a new road)' and 'Long term effects'. This literature review places an emphasis on the long term effects. Of particular importance are: how road run-off affects aquatic species populations and how associated structures, such as CSMSs, may provide new habitats for some taxa (Spellerberg 1998).

5.1. Abiotic Factors

Abiotic factors are non-living physical and chemical components of the environment (Le Viol et al. 2009). The first five factors combine to approximately give the overall water quality of the CSMSs.

5.1.1. Salinity

It has been well documented that CSMSs along roadsides contain elevated levels of salt (Forman and Alexander 1998, Le Viol et al. 2012, Le Viol et al. 2009, Scher and Thièry 2005, Marsalek 2003, Forman 2003). This is not surprising considering that sodium chloride (NaCl) is commonly used as a de-icing agent during winter (Scher and Thièry 2005, Le Viol et al. 2009, Marsalek 2003, Forman 2003, Hvitved-Jacobsen 2010, Impens 1987). Although NaCl is the most common and widely used, it is worth noting that other salts, such as calcium chloride and magnesium chloride, can be used when lower eutectic temperatures are required (Marsalek 2003). Road salts are of particular importance for Norway and the E39 highway, as temperatures usually stay below freezing for many months over winter. However, what still remains to be seen, and is not as well researched, is what effect these elevated salt levels have on the aquatic ecosystems within CSMSs.

According to Scher and Thièry (2005), aquatic organisms have a high tolerance to NaCl, unless it reaches a level where the osmotic stress becomes too great. Furthermore, in a separate study, *Gastropoda* were found to be positively affected by the higher salinity in CSMSs, with their family richness being significantly altered (Le Viol et al. 2009). These findings suggest that salinity is not too detrimental to the biodiversity within CSMSs, and for some species it may even have a positive effect, provided the levels remain reasonable.

This is in contrast with Forman and Alexander (1998), who suggest that NaCl is toxic to many species of Fish, plants and other aquatic organisms. This is an opinion shared by Marsalek (2003), who states: '*Significant environmental effects are associated with high concentrations of chloride found in receiving waters during the periods of snowmelt*.' They found that trees seemed particularly sensitive to chloride damage, in comparison to roadside grasses and shrubs. However, a study found that when the use of de-icing salts was prevented, flora harmed by salt stress were able to recover (Trombulak and Frissell 2000). Sodium was found to accumulate in the soil within five metres of the road, thus altering the plant growth (Marsalek 2003). NaCl also facilitates the increased mobility of chemical elements within soil, such as heavy metals (see section 5.1.5.), which further exacerbates another factor affecting the biodiversity along roadsides (Forman and Alexander 1998). In addition, a separate study suggested that road salts were found to effect the reproduction of Amphibians (Brand and Snodgrass 2010). Forman (2003) portrayed how confined bodies of water in basins, such as CSMSs, are especially sensitive to road salts, when they have limited water passing through them. This is because salt is able to accumulate, especially in shallow waters, forming a dense salty layer at the base. This can create permanently stratified water bodies, resulting in little to no oxygen at the base; therefore, the normally lush creation of *benthic* organisms can be excluded at the bottom of these water bodies (Forman 2003). These papers seem to indicate that any heightened levels of NaCl should be avoided if possible, as it has a very negative effect on the surrounding roadside ecosystems.

Perhaps the best outlook, when considering NaCl as a factor affecting biodiversity within CSMSs, is that different species have different levels of sensitivity and tolerance to salt (Snodgrass et al. 2008). One study explored the different effects exposure to polluted stormwater sediment had on an Amphibian species sensitive to urbanisation, *Rana sylvatica*, in comparison to a not as sensitive Amphibian species, *Bufo americanus*. The levels of sensitivity were defined by the negative relationship between urban land use and species existence. The results clearly indicated how *B. americanus* were more resilient to pollution, as they suffered non-lethal effects, in comparison to *R. sylvatica* where all embryos and hatchlings died after just 13 days. However, a limitation of this research is that the exact cause of mortality to the *R. sylvatica* was inconclusive, as it could have been either because of the heightened Cl^- ion, heavy metal or polycyclic aromatic hydrocarbons (PAHs) concentrations. Alternatively, it could have been a combination of all three of these factors (Snodgrass et al. 2008).

It is important to note that if NaCl is found to be detrimental to many aquatic species in the CSMSs along the E39 highway, then perhaps calcium magnesium acetate (CMA) could be used as an alternative de-icing agent. CMA acts better as a de-icing agent, is not as corrosive, is less movable in soil, biodegradable and is not as toxic to aquatic organisms as NaCl (Forman and Alexander 1998). To date, it has been widely used at airports to de-ice aircraft and runways. But, the main reason its use has been limited is because it is expensive and in a few exceptions applicators have been dissuaded by the vinegar-like odour of acetate (Forman 2003). However, despite an estimated cost (US$ in 2001) per ton of: $450-$600 for CMA and just $50 for NaCl, the destructive costs associated with using NaCl, such as destruction of road surfaces and corrosion of vehicles, are almost always never included in the cost of road salt. It thus raises an interesting economic paradox because when considering these secondary costs of maintenance, the actual cost of applying NaCl to roads is estimated to be around US$1600 per ton (Forman 2003).

Overall, salinity should be considered an important factor affecting the biodiversity in CSMSs. This is because on balance, there appears to be more negative implications of high salinity than positive. Furthermore, NaCl seems to impact rarer and more sensitive species, whilst common, more robust species are able to survive (Snodgrass et al. 2008). Thus, if this trend were to continue, the biodiversity within CSMSs would decline over time. Through smart use of de-icers and changing the design of CSMSs to allow chloride dilution and flows at low concentrations, environmental benefits can be readily achieved (Marsalek 2003).

5.1.2. Conductivity

Like salinity, it has been well documented that CSMSs have a higher conductivity than that of natural ponds in a wider environment (Le Viol et al. 2009, Le Viol et al. 2012, Scher and Thièry 2005). This increase in conductivity is likely to be mainly because of the salt flow into CSMSs and therefore the abundance of Cl^- ions (Scher and Thièry 2005, Brand et al. 2010). Furthermore, conductivity could also be linked to base type, as ponds with a Poly-Ethylene High Density (PEHD) membrane have been shown to have a much lower conductivity than ponds with natural bottom types. This difference in conductivity could be due to a thinner layer of sediment collecting on the PEHD bottom (Scher and Thièry 2005). There has not been much research, however, on the effect these different conductivities are having on the biodiversity within CSMSs.

One study found that conductivity was a poor predictor of frog existence, indicating that conductivity had little to no impact (Scheffers and Paszkowski 2013). This is in contrast to a separate study, which suggested that high conductivity (3000 to 5150µS/cm) may appreciably affect the survival of *Hyla veriscolor* embryos (Brand et al. 2010). However, it is worth noting that the authors believe the negative effect to be mainly a result of the heightened salt levels. Their findings are also in line with a different study, which found that Amphibian species richness was negatively correlated with water conductivity (Hamer and Parris 2011). But, they also note that the higher conductivity could be a result of the higher heavy metal and nutrient concentrations - a result of urban runoff - contained within the urban ponds.

Overall conductivity does not appear to significantly affect the biodiversity within CSMSs, but instead is a secondary effect of harmful factors such as road salts. However, if it does have any consequence on the biodiversity within CSMSs, the effect appears to be negative. But, it should not be considered as an important factor as there is little data to suggest it is the principle cause of these negative effects. Additionally, because it is a secondary effect of using road salts, by modelling salinity you are inadvertently also modelling conductivity, so there is no need to include both factors within the ecological model.

5.1.3. pH

The pH of CSMSs reviewed in the literature almost unanimously had a different value than that of the surrounding ponds. Wet ponds were found to have a higher pH than that of the natural surrounding pounds (Le Viol et al. 2009, Scher and Thièry 2005, Le Viol et al. 2012). This is in comparison to bioretention swales, in Melbourne, which were found to have a lower pH (Kazemi et al. 2011).

There were many different suggestions for what the exact cause of differing pH was. One theory for the higher pH in wet ponds was that there was not as much leaf litter in the CSMSs in comparison to the surrounding ponds. This is because they usually did not contain as much vegetation and because they tended to be surrounded by less woodland areas. The result of less leaf litter is less litter decomposition, which is known to release humic acid and thus lower the pH (Le Viol et al. 2009). Kazemi et al. (2011) suggested two potential reasons for the lower pH in the bioretention swales. Firstly, they thought it could be because of the inherent pH of the imported soil used in the construction of the swales; secondly, they hypothesised that it could be a consequence of the acidic stormwater entering the swales. The stormwater is generally acidic because it mixes with carbon dioxide and other gases in the atmosphere, thus forming acid rain (Kazemi et al. 2011). A final theory for differing pH levels could be road dust, although the effects of road dust are little-researched (Forman and Alexander 1998). Overall, the best explanation for pH differences appears to be leaf litter and the subsequent release of humic acid on decomposition. This is because this hypothesis matches all of the different data sets, as the bioretention swales contained far more vegetation than the surrounding gardenbed-type and lawn-type green spaces, and so should contain more leaf litter, thus explaining its lower pH.

Again, despite wide recognition that pH levels in CSMSs are different to surrounding ponds, little research has gone into the impact this difference has on the biodiversity of CSMSs. The comparatively lower pH in the soil of bioretention swales, in contrast to the other land use soils, appeared to positively affect above ground Invertebrates. But, the authors do note that pH could: "*act as a proxy for other habitat factors in these landscapes*" P.147 (Kazemi et al. 2011). Conversely, another study found that on the family level, species richness and diversity was as least as rich as nearby natural ponds, despite the higher pH levels. However, there was a higher occurrence of little and short life Invertebrates in the CSMSs (Le Viol et al. 2009). Therefore, both higher and lower pH values appear to have little impact on the biodiversity within CSMSs.

In summary, pH should not be considered an important factor affecting the biodiversity within CSMSs. This is because despite CSMSs containing differing pH values, the pH values usually are not too drastically different and tend to vary by around 1 point. Furthermore, different taxa have different reactions to acidity and alkalinity, with some preferring the former, some liking neutral conditions and others the later (Cárcamo and Parkinson 2001). However, in order to minimise differences in pH, more vegetation should be grown in and around CSMSs. This will help mimic the natural pond ecosystems of the E39 highways surrounding natural ponds and should help preserve the abundance of particularly sensitive species. This is discussed in further detail later in this paper (see section 5.2.1.).

5.1.4. Nitrogen Oxides

Nitrogen oxides (NO_x) concentrations are higher along roadside edges because of vehicular emissions (Cape et al. 2004). It is therefore not surprising that studies have shown stormwater ponds to contain elevated levels of NO_x in comparison to other surrounding ponds (Le Viol et al. 2012, Le Viol et al. 2009). As well as vehicle emissions, another big contributor to the NO_x concentrations within CSMSs is agriculture. This is because nitrogen is commonly used as a fertilizer for crops; therefore, CSMSs surrounded by agricultural fields are likely to have particularly elevated levels of NO_x (Scher and Thièry 2005).

A very well researched problem of heightened NO_x levels is eutrophication. Eutrophication is where the raised nutrient levels in water, as a result of nitrates, nitrites and phosphorous (another fertilizer commonly used in agriculture), lead to a boom in growth of phytoplankton and algae in surface waters (Forman 2003). The main problems this has on aquatic ecosystems are: reduced light penetration due to algae blocking out sunlight; ecosystem changes, especially within the plant community with a move from deep-rooted foliage to floating algae; a loss of oxygen in the water, as the algae consumes more oxygen, in extreme conditions it can lead to dead zones within water bodies with deeper sections becoming anaerobic; and, an increase in alkalinity caused by plants consumption of inorganic carbon (Hvitved-Jacobsen 2010). It is because of these reasons that eutrophication within any CSMSs would most likely result in a large loss of biodiversity, with many species dying out.

Nitrogen oxides have been shown, in the literature, to have a mixed effect on both vegetation and Amphibians. One study in England portrayed how nitrogen oxides positively influenced plant growth (Angold 1997). Whereas a different paper discovered signs of injuries of Norway spruce, as a result of nitrogen oxides (Coffin 2007). The later point could be of particular importance in the construction of the E39 highway. Elevated NO_x levels could negatively impact Amphibians, with wood frog presence in 74 wetlands in Ontario, Canada, adversely correlated to nutrients (Houlahan and Findlay 2003). However, Scheffers and Paszowski (2013) found the opposite in their study, with wood frog presence positively correlated to levels of Nitrogen. Additionally, nitrogen levels were found to be one of the best indicators of frog occurrence (Scheffers and Paszkowski 2013). Furthermore, stormwater ponds are known to generally have a plentiful supply of green frogs. This could be as a direct result of them reacting healthily to eutrophication and elevated NO_x levels (Le Viol et al. 2012).

Despite having a mixed effect on the biodiversity within CSMSs, nitrogen oxides do normally have an impact on aquatic ecosystems, with some studies finding it could be one of the best predictors of certain species occurrence. Therefore, it should be considered as an important factor affecting the biodiversity within CSMSs. Furthermore, dangerously high levels of NO_x must be avoided, in order to prevent the development of eutrophic conditions within CSMSs.

5.1.5. Polycyclic Aromatic Hydrocarbons (PAHs) and Heavy Metal Accumulation

"*Whereas there is much research showing rates and levels of accumulation of metals in roadside biota, the effects seem not well researched.*" P.326-327 (Spellerberg 1998). Despite being written in 1998, this is still the case today, with many researchers agreeing with this finding (Forman 2003, Hvitved-Jacobsen 2010, Karouna-Renier and Sparling 2001); however, there have been some studies that have begun to look at the impact heavy metals and PAHs have on biota (Beasley and Kneale 2002, Brand et al. 2010).

According to Karouna-Renier and Sparling (2001), the main sources of heavy metal pollution within CSMSs are: vehicular by-products, atmospheric fallout and road-top materials. Copper (Cu), Zinc (Zn) and Lead (Pb) all appear to be of particular importance to aquatic Invertebrates, with elevated levels regularly recorded in CSMSs. This is important because Cu, Zn and Pb are known to be released from highway vehicles in substantial qualities (Sternbeck et al. 2002). In Karouna-Renier and Sparling's (2001) study, they found that Cu and Zn concentrations within macro-invertebrates living in stormwater ponds were around double that of the natural surrounding ponds. However, the Pb concentration accumulation in the macro-invertebrates remained low. But, they reason that this could be a result of the high alkalinity of the ponds as Pb bioavailability rises with acidification. They also conclude that they do not know whether these heightened levels pose a hazard to wildlife communities (Karouna-Renier and Sparling 2001).

Beasley and Kneale (2002) claim that toxic accumulation in streambed sediments is the most important factor in reducing the quality of aquatic habitats. One of the main reasons for this is that harmful contaminants are able to accumulate in the sediment, whilst the water column values are barely detectable. They found that heightened Nickel (Ni) concentrations were harmful to both the survival and reproduction of aquatic fauna. They then identified PAHs, Cu and Zn as the most important contaminants that harmfully effect aquatic ecosystems. Cu appeared to have a particularly large impact on governing the community configuration, which is not surprising when populations of all main species subject to Cu concentrations as small as 5-10 mg l^{-1} have previously been shown to decline (Beasley and Kneale 2002). They stress that lethal toxic amounts differ for various species and under varying water chemistry parameters. A result of this is that there are substantial inter species differences of deadly toxic concentrations. They summarise by saying: "*Severe metal imbalances are toxic and marginal imbalances contribute to deformities and impede health*." P.264 (Beasley and Kneale 2002).

A separate study showed how polluted sediment from CSMSs had a harmful effect on the survival and growth of anuran larvae (Brand et al. 2010). Forman and Alexander (1998) describe how Fish mortality has been found to be negatively related to high amounts of Aluminium (Al), Manganese (Mn), Iron (Fe), Cu or Zn. High metal concentrations in urban runoff have also been shown to lead to elevated mortality of other aquatic organisms (Forman and Alexander 1998).

These findings are in contrast to a separate study, which suggested that both sediment and Invertebrate heavy metal concentrations were at a relatively constant level in the CSMSs studied and not accumulating (Casey et al. 2007). Furthermore, they found that threat to species inhabiting the CSMSs, from heavy metal concentrations, did not change as a function of CSMSs age (Casey et al. 2007). Other research has also found that increasing heavy metal loads did not affect species diversity or number (Spellerberg 1998).

PAHs are hydrophobic organic compounds that are widely found in environments as a result of the burning of fossil fuels and industrial procedures. PAHs are probably the most major group of organic contaminants and they have the highest potential toxicity (Beasley and Kneale 2002). Increases in PAHs concentrations are normally positively correlated with increasing traffic. Despite all of this, PAHs have not been as thoroughly studied and have received less focus than heavy metals in studies looking at water quality. However, it appears that PAHs have a negative impact on the biodiversity of aquatic ecosystems and can also accumulate like heavy metals (Beasley and Kneale 2002).

To summarise, PAHs and heavy metals seem to have a harmful effect on biodiversity and therefore are an important factor. The harmful consequences of increasing heavy metal and PAHs concentrations depend on the vastly different lethal concentrations for different taxon. Additionally, because the nutrient, heavy metal and PAHs concentrations in different CSMSs studied are highly variable, it is very challenging to make a definitive conclusion for the relevant significance of particular variables on the biodiversity within CSMSs.

5.1.6. Average Annual Daily Traffic

Forman (2003), states that high traffic volume, resulting in polluted urban runoff, has been associated with the deaths of Fish and other aquatic organisms. Other researchers have also stated that highway density and their accompanying traffic have a large adverse consequence on CSMSs occupancy and anuran richness (Scher and Thièry 2005). Thygesen (2013) found that average annual daily traffic (AADT) was the factor which affected the biodiversity in CSMSs the most. This is not that surprising considering it is a well-documented producer of PAHs, which are powerful atmospheric pollutants, and other substances such as nitrogen oxides (see sections 5.1.4. and 5.1.5.) (Forman 2003). But, what is surprising and somewhat counter intuitive is that AADT was positively correlated with biodiversity (Thygesen 2013). One potential explanation for this could be that taxa thrived within the CSMSs because of the additional nutrients in the water, as a result of the traffic (Le Viol et al. 2009). Alternatively, there could have been other factors, which Helene Thygesen (2013) did not analyse, which have a greater effect on the biodiversity within CSMSs. The following data analysis in this report may shed further light on the latter point, as two different factors are analysed, using the same data (see section 6).

In other literature assessing the impact of roads on aquatic ecosystems, AADT is not considered as a factor, but instead they look at the pollutants caused by the AADT. Therefore, the direct effects of AADT seem to have little impact on the biodiversity within CSMSs, but instead its secondary effects of increased nutrients and heavy metal concentrations have much more importance. It should not be considered an important factor, but rather the individual traffic pollutants should be considered. However, if it is difficult to measure the individual pollutants, using AADT as a leading indicator could be a cheaper and easier alternative.

5.1.7. Basin Size, Depth and Shape

The impact of CSMSs shape on aquatic biodiversity has been relatively well documented in the existing literature, especially in regards to Amphibian populations. One study found that the presence of boreal chorus frogs is adversely related to the wetland slope (Scheffers and Paszkowski 2013). Therefore, they suggest that future CSMSs should include shallow littoral zones because these will probably advantage urban Amphibians by accommodating vegetated regions for egg laying as well as environments for maturing larvae (Scheffers and Paszkowski 2013). This view is supported by Moore and Hunt (2012) who found that the inclusion of a littoral shelf was the only design factor that substantially affected the biodiversity within wet ponds. Le Viol et al. (2012) also suggest that one side of the CSMSs should have a mild slope to help encourage Amphibian occupancy. These findings are in contrast to a separate study which found that steeper slopes were associated with greater biodiversity, when looking at Invertebrate populations (Kazemi et al. 2011).

The water depth of CSMSs appears to have an impact on their biodiversity. Brand and Snodgrass (2010) found that late-stage larvae only occurred in anthropogenic wetlands and not natural wetlands. This was surprising and was a result of the natural habitats not containing adequate water long enough for the larvae to develop. However, they advise against designing CSMSs as constant water bodies because this sometimes leads to the incursion of Fish and other potential predators, which can hinder the inhabitance of many Amphibian species (Brand and Snodgrass 2010). This opinion is supported by Scheffers and Paszkowski (2013) who found constructed wetlands absent of Fish provided richer Amphibian communities and bigger populations than those with Fish. Another researcher has also found that the permanence of Amphibians depends on CSMSs drying after metamorphosis, to prevent the incursion of predatory Fish (Forman 2003).

CSMSs size seems to be positively correlated with biodiversity. One paper predicted that larger permanent and temporary freshwater bodies will contain a higher proportion of predatory taxa. This implies that these ponds will contain greater species richness and be more diverse as the amount of predatory and non-predatory species in a habitat are positively correlated (Spencer et al. 1999). A separate study found that pond area and base were positively linked with biodiversity (Scher and Thièry 2005). Significant positive correlations have also been observed to occur between wetland area and species richness (Forman 2003).

In summary, CSMSs size, depth and shape appear to have a large impact on their biodiversity. Depending on what animal family you are prioritising, it can be beneficial to have steep or shallow slopes, and likewise permanent or temporary bodies of water. It appears that the bigger the CSMSs, the greater the biodiversity within them.

5.1.8. CSMS Substrate Type

According to Scher and Thièry (2005), the base material of the CSMSs they studied appeared to have a significant effect on dragonfly species richness. They found that more dragonfly species were recorded in ponds with natural base materials, than those constructed of a man-made (PEHD membrane) base. However, the base type had little consequence on the Amphibian richness of the CSMSs. Another interesting finding was that there were lower levels of Zn in the CSMSs with natural substrates as opposed to those with PEHD membrane bases. The authors thought this may be explained by the shallow sediment cover, found in CSMSs with PEHD membrane bases, which might stop *macrophytes* from installation and thus decrease bio-remediation (Scher and Thièry 2005).

Despite CSMSs base type appearing to have an impact on the biodiversity, only one study was found that analysed its impact. But, other researchers have also suggested that modern ponds with PEHD bottoms, built to reduce pollutant infiltration, could contain differing biodiversity than ponds with a natural bottom (Le Viol et al. 2009). Therefore, because CSMS substrate type appears to be an important factor and because very little previous analyses have been carried out, the effect this factor has on the biodiversity within CSMSs has been explored further in this report (see section 6.3.).

5.1.9. Age

One would assume that the biodiversity within CSMSs would improve over time. This is because the older the ponds get, the more nature will overcome them and the more 'natural' they will become over time, as more local species begin to reside in them. However, very little research has been done to assess the impact of pond age on the biodiversity within CSMSs.

One study found a clear positive correlation between pond age and taxon richness, in CSMSs (Scher et al. 2004). Thygesen (2013) found in one Norwegian study that CSMSs exhibited far fewer species (52 taxa) when they were a few years old, in comparison to older CSMSs which had a greater species richness (116 taxa). Additionally, le Viol et al. (2009) found macro-invertebrate communities to be just as prosperous in the CSMSs studied, in comparison to the surrounding ponds, when the CSMSs had been built around 34 years ago. This would suggest that the older the ponds became, the more diverse they were likely to become. It is because of the positive influence pond age seems to have on biodiversity within CSMSs and the large lack of research into the influence of this factor, that it has been further analysed in this paper (see section 6.2.). Furthermore, additional investigation is required to help deduce whether or not it is deemed one of the most important factors affecting the biodiversity within CSMSs.

5.1.10. Noise

According to Coffin (2007), heightened noise levels are one of the major environmental consequences of road construction, and they cause an irritation to both urban and suburban human populations. As a result, noise mitigation usually forms a large part of any highway construction project budget. Despite this, the consequences of road noise on wildlife populations has not been comprehensively studied (Coffin 2007).

Road noise can, however, have an impact on the ecosystems surrounding roads. It appears to have the greatest impact on species which inculcate sound into their everyday behaviour, for example Birds (Coffin 2007). Due to the daily fluctuations in road noise with time, there could be varying effects of road noise on animals, dependent on the time of day or season, and subject to the daily living patterns of the animal. Furthermore, if the frequency of an animal’s call interferes with the road noise frequency, the effect of the road noise will have a far greater impact on the animal (Coffin 2007). Indeed many studies have indicated that road noise has a negative effect on some Bird populations, and as a result they tend to nest further away from roads (Polak et al. 2013, Arévalo and Newhard 2011, Peris and Pescador 2004).

Perhaps more importantly for CSMSs, it has been shown that road noise level could be negatively correlated to anuran populations (Eigenbrod et al. 2009). This is again probably because of the interference between road noise frequencies and anuran's mating calls; interestingly, the negative correlation is far higher than the effect of road-kill on anuran populations (Eigenbrod et al. 2009).

Thus, noise level does appear to have a negative effect on both roadside and CSMS biodiversity. Therefore, it should be considered as an important factor affecting the biodiversity within CSMSs, especially when modelling Amphibian populations.

5.2. Biotic Factors

A biotic component is a living or once living factor of a habitat (Le Viol et al. 2012).

5.2.1. Vegetation

Vegetation plays a vital role in ecosystems all around the globe (Tuomisto et al. 1995). A varied collection of foliage should be more productive than a monoculture. This is intuitive because the larger the variation in vegetation, one would assume the greater and more diverse number of taxa it can support. Probably for the same reason as increased productivity, species often show greater resilience to invasion within diverse plant communities (Purvis and Hector 2000). However, what still remains to be seen is what impact localised vegetation has on the biodiversity within CSMSs.

Researchers have highlighted the importance of preserving all natural woodland along the ridges of highways, during their construction (Le Viol et al. 2009, Scheffers and Paszkowski 2013). This is because surrounding land use of CSMSs plays an important role in defining their suitability as a habitat for Amphibians (Scher and Thièry 2005). Surrounding land use has been shown to be statistically relevant to the biodiversity within CSMSs (Scheffers and Paszkowski 2013).

As well as surrounding vegetation, some academics have found that vegetation within CSMSs has a positive impact on their biodiversity. In bioretention swales, the mid-stratum vegetation layer increased Invertebrate numbers, species richness and diversity, despite its primary design function of encouraging biological uptake of water pollutants (Kazemi et al.

2011). This is probably because the layer of foliage forms a favoured habitat above the ground for the Invertebrates, providing them with shelter (Kazemi et al. 2011). This is in-line with a separate study which found that potential habitats within constructed wetlands could be improved by encouraging the development of emergent and submerged water plants (Scheffers and Paszkowski 2013). The authors found emergent foliage was positively correlated with wood frog appearance. Furthermore, both foliage densities were positively linked with boreal chorus frog numbers (Scheffers and Paszkowski 2013). However, wood frog occurrence was found to be negatively correlated with submerged vegetation. This again highlights the different preferences and sensitivities of different species to habitat conditions, but overall both types of vegetation had a positive impact on anuran occurrence (Scheffers and Paszkowski 2013). These findings are in contrast with Thygesen (2013), who found no correlation between vegetation, growing within the basin or on the edges of wet ponds, and biodiversity.

Overall, vegetation does seem to have a positive impact on the biodiversity within CSMSs. Therefore, it should be considered as one of the most important factors affecting the biodiversity. Furthermore, it is important to note that the planting of many heterogeneous local plant species should be encouraged during the planning phase. Different plant combinations should be considered for each separate CSMS, which should further increase the regional biodiversity between the CSMSs.

5.2.2. Human Influence

In this paper, human influence is defined as the impact of direct human access to CSMSs. The effect that human influence has on the biodiversity within aquatic ecosystems has had virtually no mention, within the existing literature. Scher and Thièry (2005) found that Amphibians tended to be negatively associated with the extent of anthropisation. This is with the exception of opportunistic marsh frogs which were suggested to be highly anthropophilous (Scher and Thièry 2005). The paper also highlighted how human access and disruption effects, to isolated places, tend to escalate with higher road densities (Scher and Thièry 2005).

One would assume that human influence has a slightly negative (if any) impact on the biodiversity within CSMSs. However, it is almost impossible to quantify and no conclusive research has targeted this issue. Therefore, it should not be considered as one of the most important factors affecting the biodiversity within CSMSs.

6. Data Analysis

This section analyses two of the factors reviewed (see section 5) using Helene Thygesen's (2013) existing data, collected as part of the NORWAT project.

6.1. Methods used for the analysis

The following subdivision outlines and explains the analytical tools, methods and data used in the data analysis.

6.1.1. Principal Component Analysis (PCA)

PCA is a form of multivariate statistics that can include multiple statistical variables in an analysis (Shaw 2003). It was used to analyse the two factors reviewed, whilst encompassing other important factors, to provide a more accurate description of their relative importance. It would have been overly simplistic to solely use univariate statistical analysis because nature is a highly complex system with a plethora of vastly different factors having an impact on the biodiversity within specific habitats. Thirteen factors in all were included in the complete PCA analysis, 12 of which were quantitative variables and 1 qualitative (base type).

PCA works by first converting each variable into a new dimensionless variable. This is achieved through normalisation, transforming the data so that its mean becomes zero and its standard deviation becomes one. After this has been done, one is able to plot n variables in an n dimensional space along two uncorrelated (orthogonal) fictional axes. The two axes describe the correlation of data, with the PCA principal axis 1 (horizontal) representing the highest correlation and PCA principal axis 2 (vertical) the second highest. The two axes combine to give the overall PCA plot correlation. A graphical representation of the formation of the PCA principal axes is shown by figure 3. Variables are then displayed in the ordination plot as arrows; with the angle between two separate arrows (variables) approximating to the linear correlation coefficient and the magnitude of the arrows portraying their importance. The distance between points indicates their similarity or differences. Finally, the quantitative value of a specific variable can be roughly read from the graph, by comparing the plotted point's orthogonal location from the arrow. For most environmental scientists it is the primary ordination technique used (Shaw 2003).

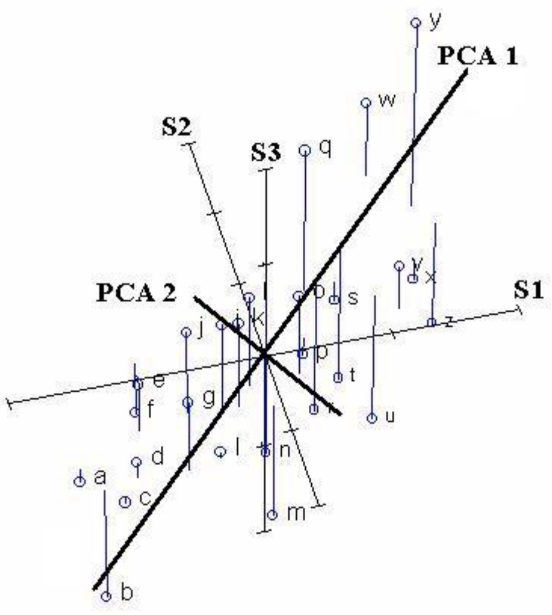

Figure 3: Formation of the PCA principal axes, labelled PCA 1 and PCA 2. S1, S2 and S3 are the standardised axis, with their intercept indicating the centroid. The other lettered points are indicative of random sample data points (Palmer 2014).

6.1.2. Nonlinear Regression

Nonlinear regression was used to analyse CSMSs age against Shannon Diversity Index (SDI). Nonlinear regression was used, as opposed to linear, because there was no statistically significant linear relationship between the two variables. Therefore, nonlinear regression was performed, until the pre-programmed function that best described the data was found. This was achieved through an iterative process, using XLSTAT software (XLSTAT 2013).

6.1.3. Box Plots

Box plots were used for the univariate analysis between CSMSs substrate type and the two measures of biodiversity (species richness and SDI), looked at individually. The minimum and maximum points are connected by the whiskers, with anomalies left as unattached points. The horizontal lines are indicative of the quartile ranges, with the central line the median, the upper quartile the top line and the lower quartile the bottom line. The mean is portrayed as a red cross (XLSTAT 2013).

6.1.4. Measures of biodiversity: Species Richness and Shannon Diversity Index (SDI)

During the analyses, two measures of biodiversity were reviewed. The two measures used were: species richness (total number of different species present) and the Shannon Diversity Index (SDI) (Jost 2006). It is worth reiterating, that the two selected measures of biodiversity evaluated are two of many different measures of biodiversity (see section 3.1.).

The species richness is the total number of different species present within an ecosystem, and it is the most commonly used measure of biodiversity (Purvis and Hector 2000). It was calculated by adding up the total number of different taxa observed across all of the readings taken by Helene Thygesen (2013).

The SDI, Shannon entropy or 'H' is frequently used as a measure of biodiversity (Spellerberg and Fedor 2003). It is a quantitative measure of biodiversity and combines both the species evenness and richness. Species evenness is how fairly the number of taxa observed are spread across different species (Thygesen 2013). Another way to think of SDI is as a measure of entropy. Entropy is the degree of randomness and disorder within a system (Jost 2006). The Shannon entropy calculates the uncertainty in forecasting the identity of an individual species, taken randomly from a data set. Thus as the SDI approaches 0, the less diverse an ecosystem is (i.e. there is no uncertainty in predicting which species are found as there is only one species in the ecosystem) (Jost 2006). The formula for the SDI is shown below, where n is the number of species observed and p_i is the theoretical probability of existence of species i (Izsák 2007):

$$H = -\sum_{i=1}^{n} p_i \ln p_i \qquad (1)$$

6.1.5. Input Data

Table 1 provides an overview of the calculated species richness, SDI, age and CSMSs base type used in the PCA analysis of the nine wet ponds, located within the Oslo region in Norway. Additional data that were used to complete the PCA analyses were: pond size, chloride concentrations (a measure of water quality) and sediment chemical data (the percentage of dry matter, loss of ignition, Cu, Zn, Al, PAHs and Pb concentrations). The percentage of dry matter and the loss of ignition combine to give a measure of the organic matter within the ponds. Sediment chemical data are used to describe the heavy metal and PAHs concentrations because some research has shown it to be more dependable and important than water column data (Beasley and Kneale 2002). A complete table of the input data is portrayed in appendix A. These factors were selected to give an approximate overview of the perceived main factors, based on the literature review, involved in determining the biodiversity within CSMSs; as using two factors to model a complex system would be overly simplistic and highly inaccurate (see section 6.1.1).

It is important to note that the number of samples taken only affects the species richness and not the SDI. The fact that different numbers of samples were taken at each of the nine ponds studied could lead to anomalies within the results for the species richness as it is not normalised; therefore, you will probably find more taxa when you take more readings. The number of samples taken was not used in any of the PCA analyses, but is included for completeness (table 1) and to highlight one major shortcoming of the fauna data provided by Helene Thygesen (2013).

Table 1: The age and substrate type of each pond and their respective SDI and species richness values.

Wet Pond Name:	**Species Richness (No. of Samples[a]):**	**SDI:**	**Main Basin Base Type:**	**Age[b] (Years):**
Skullerund	35 (20)	1.64	PEHD Membrane	12
Taraldrud North	42 (19)	2.04	PEHD Membrane	9
Taraldrud Crossing	32 (20)	1.44	PEHD Membrane	9
Taraldrud South	33 (20)	1.11	PEHD Membrane	9
Nostvedt	29 (20)	1.62	Concrete	4
Vassum	43 (20)	1.21	Clay	13
Enebakk	31 (9)	1.88	PEHD Membrane	9
Idrettsveien	37 (23)	2.13	Clay	8
Nordby	54 (24)	2.02	Clay	8

a) The total number of taxa samples collected, from four separate sampling occasions, during 2013.
b) The age of the ponds when the data were collected in 2013. Also, Skullerund was built in 1999, but was re-sealed with a PEHD membrane in 2001, hence its age is given as 12 not 14.

The calculated SDI is high if many different taxa were found in a particular pond with many species being dominant. Alternatively the SDI is low if few taxa are found and one of the species is completely dominant (Thygesen 2013). Six of the ponds had a SDI considered low (between 1.48-2.22) and three of the ponds had a very low (≤1.48) SDI (SWEPA 2000). It is also worth noting that the SDI in Idrettsveien is very close to having a moderately high index value (2.22-2.97) and Taraldrud Crossing even closer to having a low index value. Therefore, although the diversity in the ponds is not considered high, the ponds can still support a relatively diverse amount of fauna.

6.2. Effect of the CSMSs age on the biodiversity within CSMSs

The first PCA that was carried out assessed the impact of pond age on species richness (figure 4). Therefore, SDI and substrate type were not included in the analysis. In figure 4 it can be seen that CSMSs age is very positively correlated with species richness. This was in line with the literature review, that indicated that biodiversity within CSMSs generally increased with CSMSs age (see section 5.1.9.).

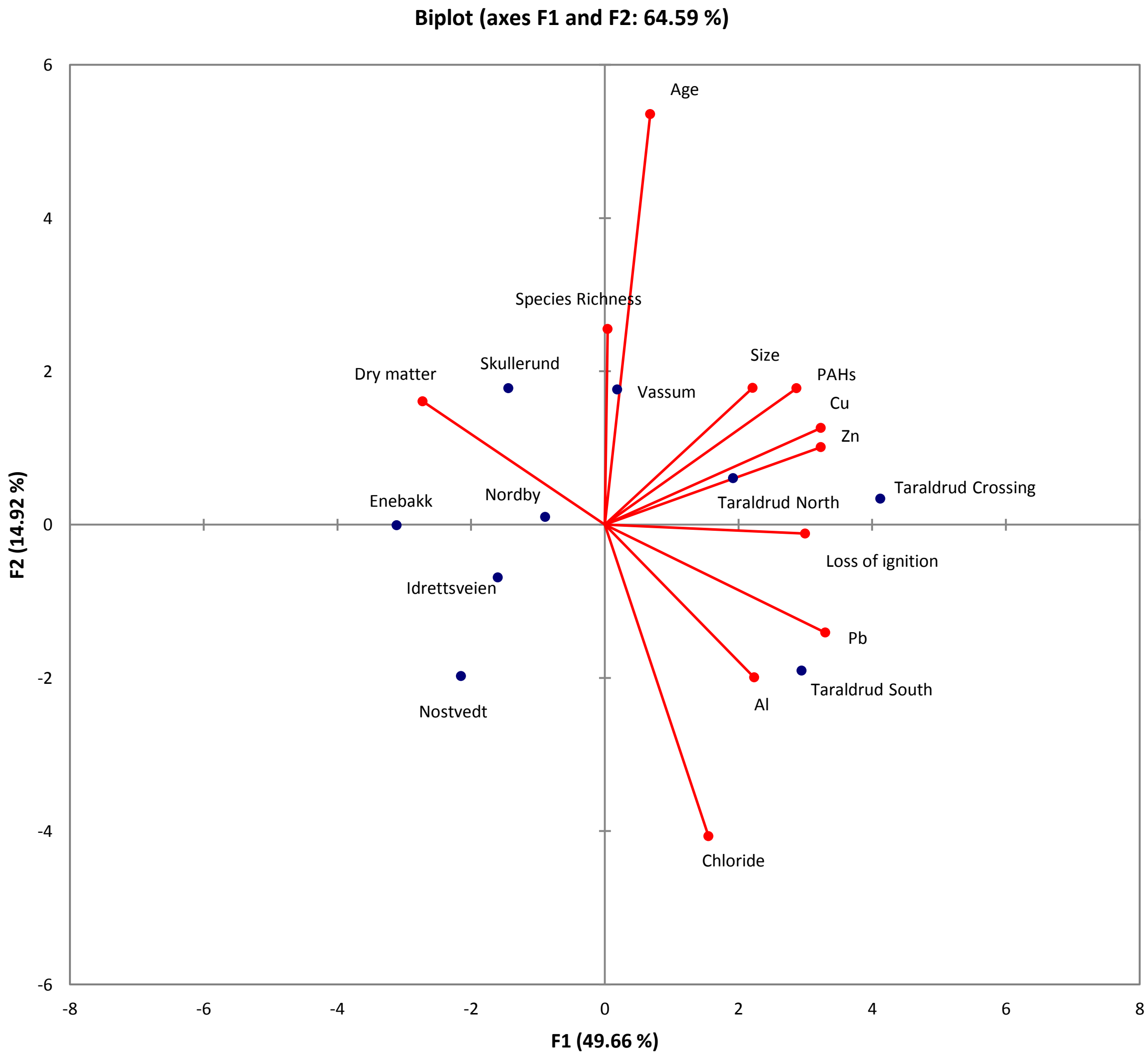

Figure 4: PCA to assess the impact of pond age on species richness.

Helene Thygesen (2013) concluded that the high species richness was positively correlated with AADT; furthermore, that AADT was the best factor to predict the species richness. However, as initially thought (see section 5.1.6.) age could instead be a more important factor. Age was not considered in her analyses (Thygesen 2013). Vassum was highlighted as a very species rich pond, and thus she concluded that this could be the reasoning for the strong correlation with AADT as it was adjacent to the busiest road (Thygesen 2013). But, as indicated by figure 4, Vassum is also the oldest pond. However, it is important to note that AADT was not included within the analysis in this paper, as heavy metal and PAHs concentrations were used instead to portray the pollution caused by traffic. But, this means that additional nitrogen oxides added to the ponds through vehicular emissions have not been included. However, as aforementioned (see section 5.1.4.), some researchers feel that the use of nitrogen and phosphorous as fertilizers in agriculture are the biggest source of nutrients within ponds.

Figure 4 shows how chloride concentrations are very negatively correlated with species richness. This is in general agreement with the literature (see section 5.1.1.) and provides evidence that alternatives to NaCl, used to de-ice the roads, should be considered. Overall, the PCA explains the data with a 64.59% correlation. Therefore, there is still a 35.41% uncertainty within the PCA, but it provides an accurate explanation of the factors affecting species richness within the ponds.

A second PCA was performed to assess the impact that CSMS age had on the SDI of the ponds (figure 5). The factors that were not included in this PCA were: species richness and substrate type. This PCA provided a very contrasting picture, to that of figure 4. Instead of indicating a positive relationship between SDI and age, the opposite is shown. This implies that the older the ponds get, the less diverse they become in terms of the SDI; thus, is in disagreement with what was found in the literature (see section 5.1.9.). Additionally, figure 5 seems to show that SDI is positively correlated with chloride concentrations, which is again the opposite of what was found in figure 4.

Figure 5 also shows the negative consequences of heightened Cu, Zn, Al and PAHs concentrations. They seem to be negatively correlated with SDI, which is as expected after the literature review, as they are known to be toxic and lethal at high concentrations.

Furthermore, as previously stated, the lethal concentrations are different for each species, with highly vulnerable and delicate species likely to have very low lethal concentration levels (see section 5.1.5). Therefore, the harmful effects of heavy metals and PAHs on biodiversity are more likely to be visualised when comparisons are made with the SDI rather than species richness. This is because unsusceptible and resilient species will be able to flourish in these conditions, whilst weaker more susceptible species will struggle and therefore reside in very small numbers.

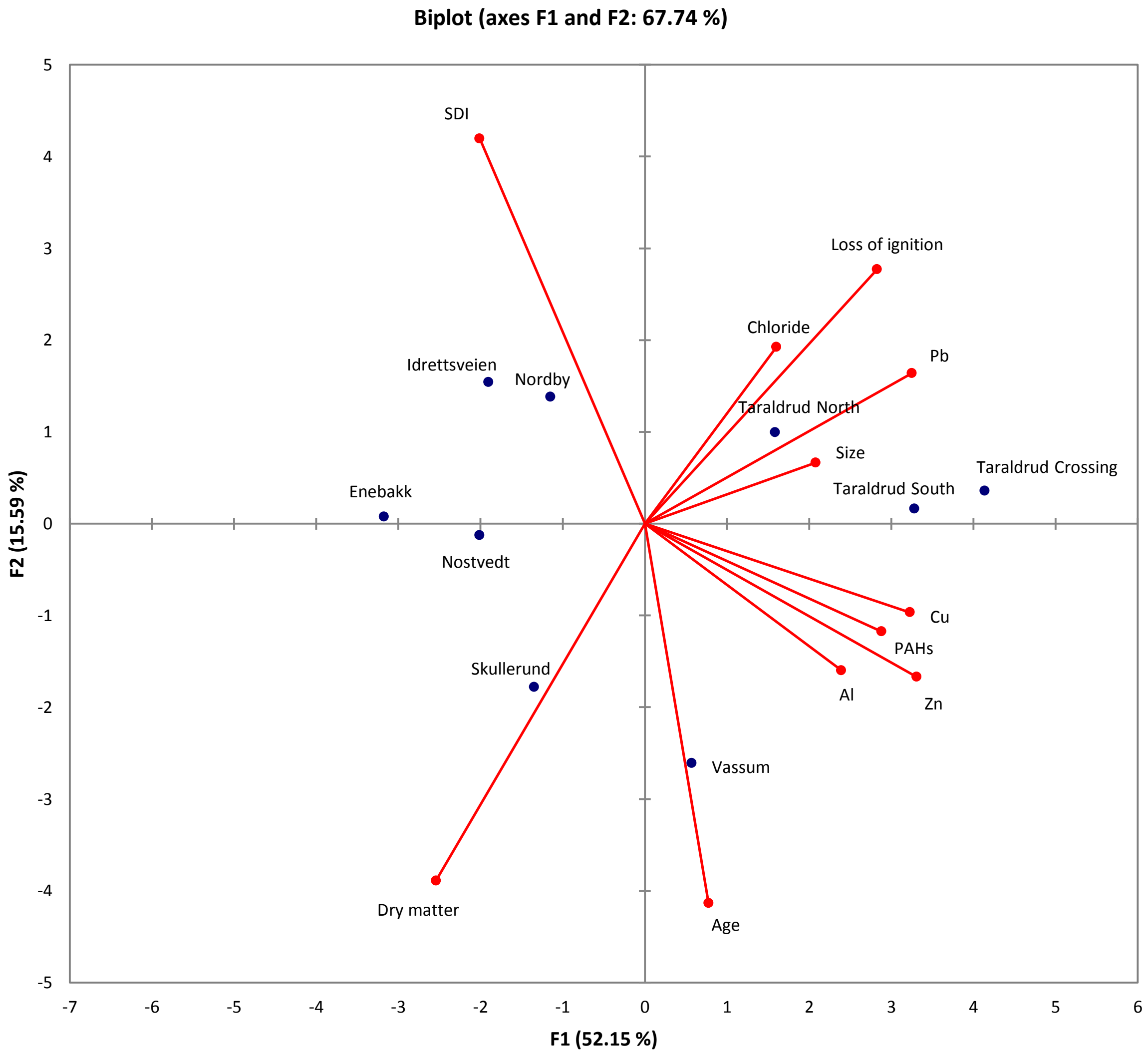

Figure 5: PCA to assess the impact of pond age on SDI.

To explain the surprising finding of age negatively affecting the SDI of the ponds, a direct comparison of pond age against SDI was performed (figure 6). The best correlation that could be found was using a polynomial line of best fit. This seems to imply that in the short term age is positively correlated with the SDI; however, in the long term it is negatively correlated. One explanation for this could be that initially new species are integrated into the pond each year, after it is newly built, with taxa that rely on a passive dispersal, such as snails, arriving in the ponds over time. However, with time, the heavy metal concentrations accumulate until they reach toxic and fatal levels for the most sensitive species. Thus, although the total numbers of organisms in the pond continue to grow, the vulnerable species begin to die out, resulting in the SDI decreasing with time and the ponds becoming less diverse.

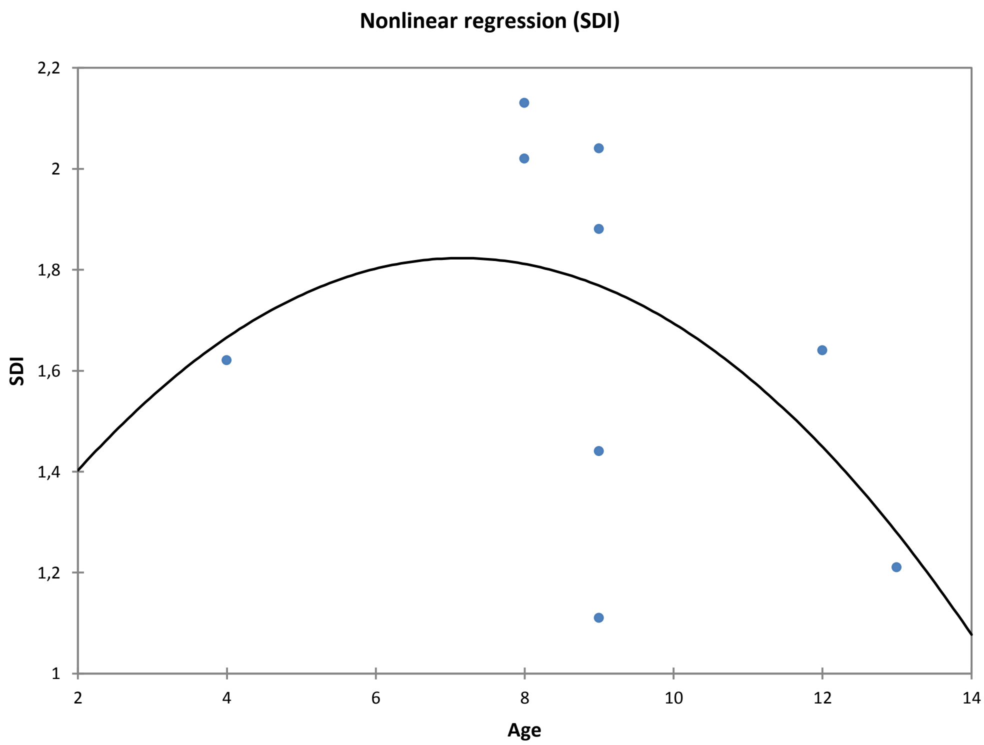

Figure 6: Nonlinear regression of SDI against pond age.

It is important to note that there are many shortcomings with this finding. Firstly, the correlation coefficient (R^2 value) was only 0.256, despite it being the most precise line of best fit. Secondly, the ponds are all very similar in age apart from three outliers (one of the main reasons for the low R^2 value), resulting in a very condensed and small range. Thirdly, it is far too simplistic to eliminate all of the other abiotic factors, such as heavy metal concentrations, because the abiotic conditions in each of the ponds are very different (see appendix A) and combine to give the overall biodiversity. Therefore, a more detailed research needs to be carried out to prove or disprove this hypothesis (see section 8), but it could help provide some useful answers towards modelling the biodiversity of these CSMSs.

6.3. Effect of the CSMSs substrate type on the biodiversity within CSMSs

The effect of substrate type on the biodiversity within CSMSs was analysed by using the same data collected by NORWAT (see section 6.1.5.) and through PCA analysis. The PCA used to describe the impact of base type on biodiversity combined all of the factors shown in appendix A. This is because, unlike in the pond age analysis (see section 6.2.), when modelling substrate type against species richness or SDI separately, the PCA's were very similar; therefore, the two measures of biodiversity have been included in the same PCA. Thus, SDI and species richness were used together to display the effects that different base types had on the biodiversity within the ponds (figure 7).

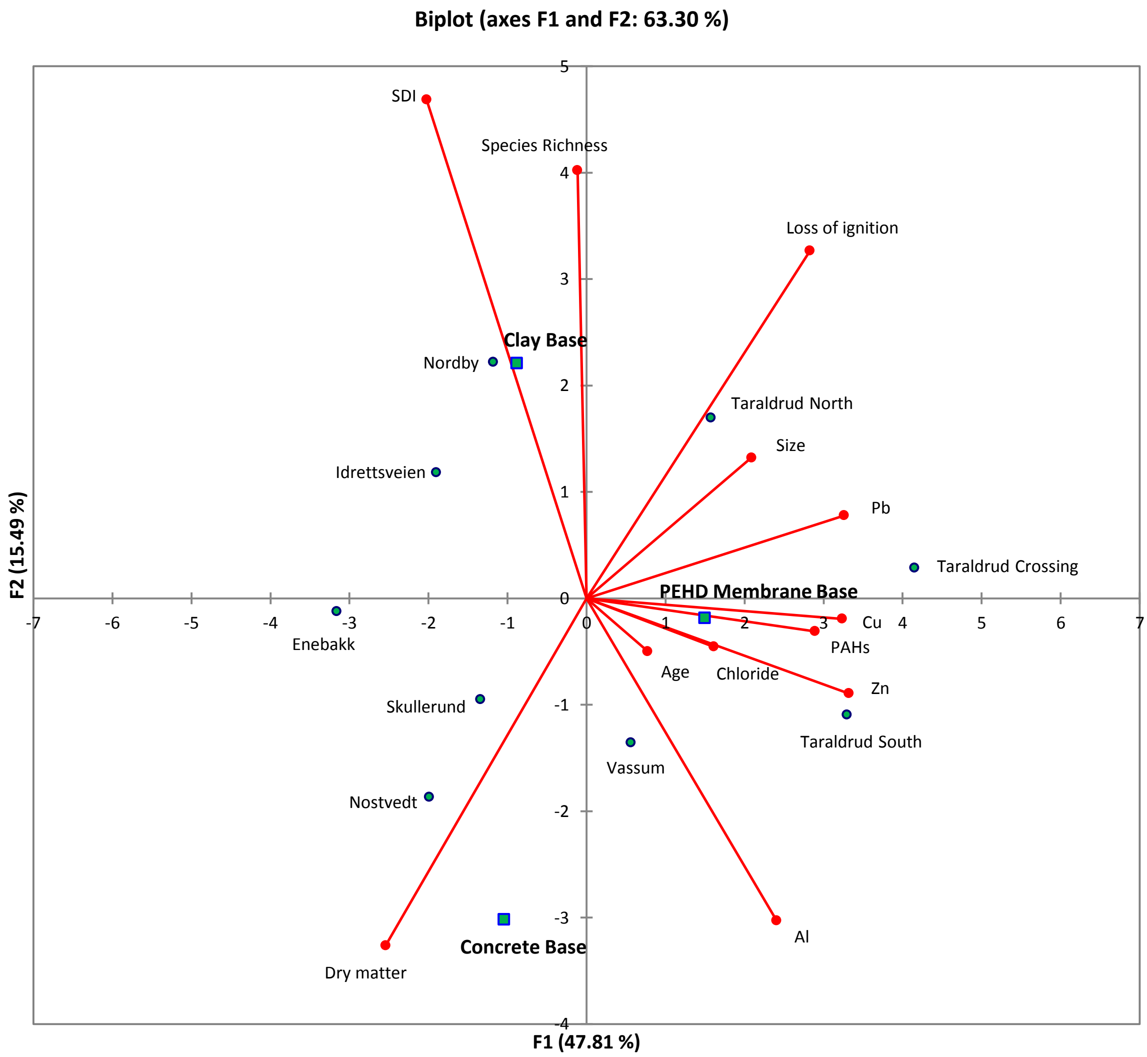

Figure 7: PCA to assess the impact of substrate type on SDI and species richness.

Clay (natural) bases appear to have a positive correlation with the biodiversity within the ponds because both the SDI and species richness are positively associated with them (figure 7). This is in contrast to concrete bases which are negatively associated with both measures of biodiversity (figure 7). But, it is unreliable to completely trust this finding because only one of the ponds analysed had a concrete base, whereas five ponds had a PEHD membrane base and three a clay base. Therefore, it is not a fair test and the concrete pond could be an anomalous result. PEHD membranes appear to be slightly negatively correlated with biodiversity as well, although there is practically no correlation (a very slight negative relationship) between PEHD membrane base type and species richness.

PEHD membranes appear to be positively correlated with heavy metal and PAHs concentrations (figure 7). This agrees with Scher and Thièry (2005), who found that there were higher levels of Zn in ponds with a PEHD membrane, potentially because PEHD bottoms tended to have a smaller sediment layer and thus the effect of bio-remediation could be reduced (see section 5.1.8.).

Univariate analysis was also used to help analyse the effects of base types on the biodiversity within the ponds. Figure 8 shows box plots comparing SDI and species richness against CSMS base type. As stated in the previous section (see section 6.2.), univariate analysis is likely to be very unreliable because of the complexity of biodiversity within nature and the multitude of factors involved. However, the box plots appear to agree with the findings of the PCA; therefore, base type does appear to affect the biodiversity of CSMSs, with clay bases supporting the highest biodiversity, followed by PEHD membrane bases and then concrete bases (figure 8).

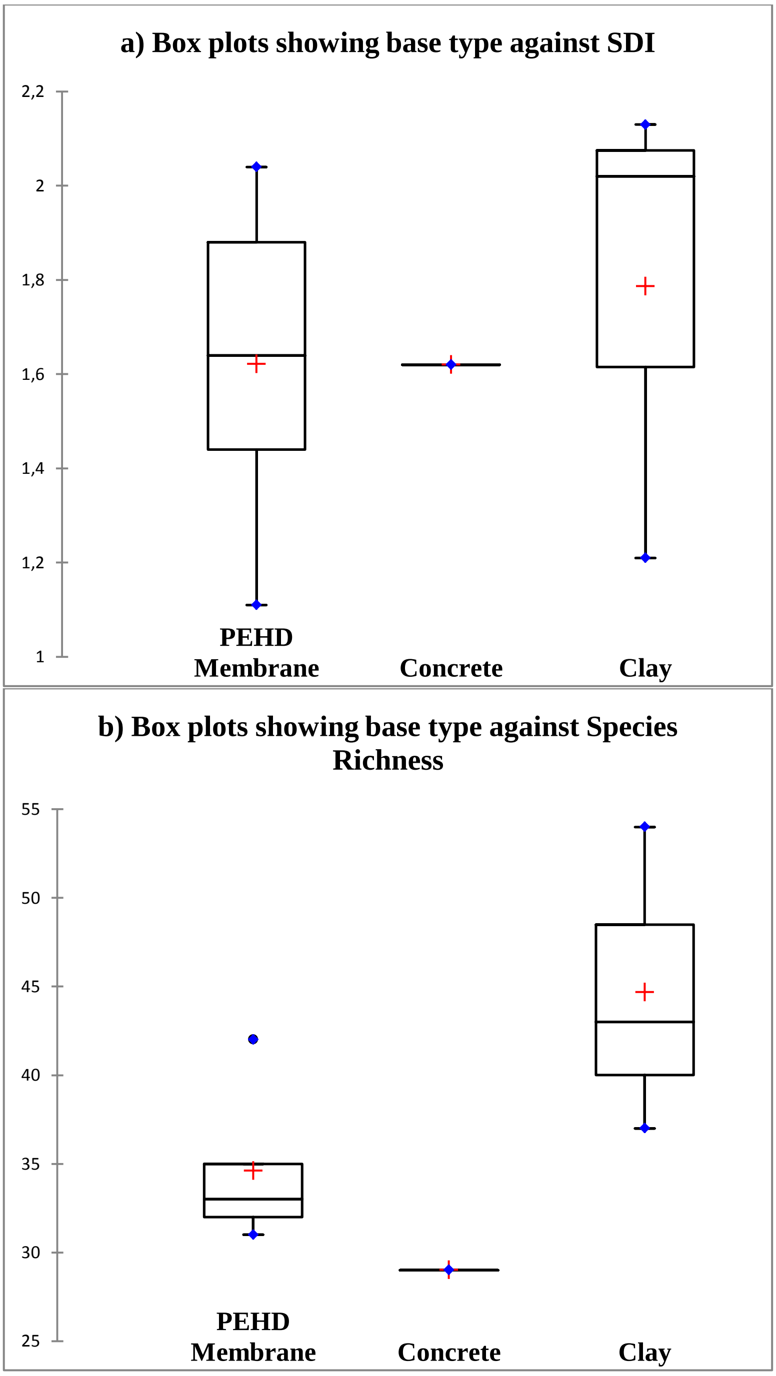

Figure 8: Box plots comparing pond base type against a) SDI and b) species richness.

7. Discussion

Although lots of research has been done on the pollutants that arise from roads (see section 5), much more needs to be done to link this to the biodiversity in aquatic ecosystems. Furthermore, these studies should attempt to isolate specific factors, instead of focusing on all of the pollutants in CSMSs. Moreover, it would be much easier to decide exactly which factors play the most important role in shaping the biodiversity within CSMSs.

As well as trying to study individual factors, these studies should be at the family level and not attempt to study the total biodiversity within CSMSs. This is because as this report has shown (see section 5), different species have contrasting tolerances and sensitivities to the various factors. One example of this is that Invertebrates favour steep sloped CSMSs, whereas Amphibians prefer gentle sloped CSMSs (see section 5.1.7.). A potential solution to this problem would be to build the CSMSs, along the E39 highway, with three slopes of the standard 1:3 ratio and one shallow slope. This would allow easier access and egress to the CSMSs for Amphibians. However, an even better alternative would be to have different CSMSs designs, some specialised for Amphibians and others for Invertebrates, Birds or Fish.

If the polynomial relationship between CSMSs age and biodiversity is found to be true (see section 6.2.), then this may lead to a future implication for the operation and maintenance of CSMSs. Figure 6 seems to suggest there is a peak in pond diversity when the pond is around seven years old. Therefore, a future suggestion would be to empty the ponds more frequently, perhaps every eight years as opposed to the current practice of emptying them approximately every fifteen years. This would help prevent lethal heavy metal concentrations accumulating.

One of the problems of heavy metals accumulating in CSMSs is that the CSMSs can then act as sinks instead of subsidies for biodiversity. A sink is defined as a habitat that appears desirable but in-fact is lethal and acts as an ecological trap (McCarthy and Lathrop 2011). McCarthy and Lathrop (2011) found that in their sample of 36 CSMSs, with permanent bodies of water, the CSMSs appeared to act as sinks for *P. crucifer* and *H. versicolor*, two amphibian species. Therefore, they concluded that effective management and planning of CSMSs is crucial to ensure CSMSs become useful habitats instead of sinks for taxa (McCarthy and Lathrop 2011). This view is shared by other authors, who suggest that by using biodiversity-friendly management methods for CSMSs, they can enhance the biodiversity in some landscapes (Le Viol et al. 2012, Brand and Snodgrass 2010).

To support this opinion, a separate study has shown that the biodiversity within six CSMSs was just as high as the surrounding ponds, when the heavy metal and toxic substance accumulation was not very severe (Scher et al. 2004). The authors suggested that CSMSs can not only act as effective habitats for aquatic and Amphibian species, but can also increase the connectivity between separate aquatic ecosystems. This is because in the area studied (in Southern France) the CSMSs had to be built at one to three kilometre intervals along the roads (Scher et al. 2004).

The discovery that CSMSs with clay bases contain a higher biodiversity than CSMSs with PEHD membrane bases; and the fact that PEHD membranes are more likely to contain higher heavy metal concentrations, presents an interesting dichotomy. This is, should the biodiversity of these ponds be prioritised, by building them with natural bases, or should the functionality of reducing the pollution infiltration to the wider surrounding environment be prioritised, by constructing the CSMSs with impermeable PEHD membranes? One would assume that the latter would be prioritised, because the primary purpose of CSMSs is to reduce the pollution levels to the broader environment.

Interestingly, some authors' feel that CSMSs should not be used as ecological systems, as highlighted by the following quote: "*A wet pond will over time typically be populated with plant and animal species. It is, however, important to stress that it is a treatment device that should remain as such that authorities should not convert it to an ecological system and define corresponding criteria."* P.261 (Hvitved-Jacobsen 2010). Personally, the author of this current report disagrees with this point, as CSMSs can benefit regional biodiversity, as previous researchers have shown (Brand and Snodgrass 2010, Kazemi et al. 2011, Le Viol et al. 2012, Le Viol et al. 2009, Scher and Thièry 2005, Thygesen 2013, Scher et al. 2004). However, Hvitved-Jacobsen (2010) is suggesting that ecological criteria should not detract the CSMSs away from their initial purpose of reducing the pollution to the surrounding environment. But, it is an old fashioned and out-dated viewpoint, because when trying to achieve sustainability, the environment and nature must always be considered. This is because it is one of the three pillars of sustainability (economic, social and environmental) which all must be considered of equal importance to achieve long-term sustainability (Bond et al. 2012).

Additionally, without researching the ecosystems of CSMSs unforeseen damages could occur as a consequence, such as bioaccumulation. Bioaccumulation is where toxic substances persist and amass within organisms. It can occur through three processes: direct uptake from polluted waters through skin or gills (biocencentration), through consumption of suspended toxic particulates (ingestion) or by eating contaminated organisms along the food chain (biomagnification) (Van der Oost et al. 2003).

Some authors think that instead of building expensive wet ponds, which are due to be built along the E39 highway, other forms of CSMSs considered in this thesis (see section 3.2.), may be just as effective and perhaps much cheaper (Forman and Alexander 1998, Kazemi et al. 2011). Forman and Alexander (1998) state: "*Instead of expensive detention ponds and drainage structures to reduce runoff impacts, creative grassland designs by roads, perhaps with shrubs, may provide both sponge and biodiversity benefits*." P.221 Kazemi et al. (2011) found that not only were more species present in the bioretention swales studied, in comparison to gardenbed-type and lawn-type green spaces; but also that they had greater diversity according to the SDI and Margalef's species richness, within their surveyed area in Melbourne. They conclude that converting conventional grass banks along streets to bioretention swales has encouraging potential for improving urban biodiversity. Furthermore, this heightened biodiversity can increase public well-being and quality of life, whilst lessening the psychological stresses linked to urban habitats (Kazemi et al. 2011).

8. Suggestions for future research

As aforementioned (see section 7), more research needs to be performed to link road pollutants to their effect on biodiversity. This should be mainly carried out at the family level, because different species have varying degrees of sensitivity to the plethora of toxic substances found along roadsides. The greater the knowledge of the consequences that these substances have on aquatic ecosystems, the more effective management and mitigation techniques can be implemented for the future operation of CSMSs.

One example of these studies would be a study to determine the impact of water conductivity on macro-invertebrate biodiversity. This would be very beneficial, in order to deduce whether conductivity has a big impact on the biodiversity of CSMSs or not. In current literature, when conductivity was positively correlated with reducing Amphibian numbers or larvae development, other factors were also present, such as heavy metals (see section 5.1.2.).

Furthermore, Amphibians have been shown to be vulnerable to even slight habitat and environmental changes (Scher and Thièry 2005). Therefore, by investigating macro-invertebrates it may provide a better understanding of the overall role that conductivity has to play in the biodiversity of aquatic ecosystems. Indeed, one article also stated that macro-invertebrates provide a more powerful gauge of biodiversity than vertebrates (Kazemi et al. 2011).

In order to determine the exact consequence that the age of the ponds has on their biodiversity, a detailed study should be carried out. One proposal could be to collect taxa data biannually from around twenty ponds, for fifteen years. Then you would be able to portray the changes in diversity of each pond individually, as they age, and also of all the ponds cumulatively. Thus you should be able to determine whether there is any validation with the hypothesis of a polynomial relationship between age and CSMSs biodiversity, outlined in this report (see section 6.2.).

9. Conclusion

There is no single, ideal design for CSMSs to satisfy every species, owing to the dynamics and complexity of nature. The natural habitats of various Plants, Amphibians, Birds, Mammals, Invertebrates and Fish are all markedly different. Therefore, when it comes to the modelling stage of the biodiversity within CSMSs, I would suggest modelling at the Family level. Furthermore, multiple CSMSs designs should be formulated, in order to move away from homogeneity and towards heterogeneity; therefore, increasing the overall biodiversity across the E39's CSMSs.

The data analysis appeared to indicate that both CSMSs age and base type have a significant impact on the biodiversity within the CSMSs. The age of the CSMS could have a polynomial relationship with the biodiversity, with it initially increasing with time, until the metal concentrations become too high, resulting in vulnerable species dying and thus the biodiversity decreasing. However, more research and data collection is required to prove this hypothesis. Clay bases appear to support the highest biodiversity, with PEHD membranes having a slightly negative impact and concrete bases having a very negative effect on the biodiversity.

As this report shows, many of the factors affecting the biodiversity within CSMSs are interlinked and interrelated. Furthermore, in any body of water, whether natural or anthropogenic, there is a multitude of factors influencing the biodiversity. Therefore, it is very challenging to decipher exactly what the most important factor is, especially when the majority of existing literature focuses on the effects of the total roadside pollution on biodiversity. The factors which appear to affect biodiversity in CSMSs the most are: salinity; pond size and shape; vegetation; age; CSMS base type; nitrogen oxide concentrations; noise; and PAH and heavy metal concentrations. Moreover, all factors in a complex system will have some sort of an impact, and some of these impacts may not initially be obvious; therefore, the more factors that can be inculcated into the modelling process the better.

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11. Appendix

11.1. Appendix A-Complete input data used in PCAs[a]

Wet Pond Name	Species Richness (No. of Samples)	SDI	Main Basin Base Type	Age[b] (Years)	Size (m^2)	Dry matter (m-%)
Skullerund	35 (20)	1.64	PEHD Membrane	12	910	48
Taraldrud North	42 (19)	2.04	PEHD Membrane	9	780	14
Taraldrud Crossing	32 (20)	1.44	PEHD Membrane	9	1400	9.1
Taraldrud South	33 (20)	1.11	PEHD Membrane	9	474	12
Nostvedt	29 (20)	1.62	Concrete	4	340	45
Vassum	43 (20)	1.21	Clay	13	363	47
Enebakk	31 (9)	1.88	PEHD Membrane	9	132	35
Idrettsveien	37 (23)	2.13	Clay	8	745	38
Nordby	54 (24)	2.02	Clay	8	389	19

Loss of ignition (550 °C % dw)	Cu (mg/kg dw)	Zn (mg/kg dw)	PAHs (sum 16 US EPA) (mg/kg dw)	Al (mg/kg dw)	Pb (mg/kg dw)	Chloride (Cl^-) (mg/l)[c]
6.7	110	420	1.2	16000	23	172
20	200	690	4	18000	27	246
20	190	800	12	20000	34	306
18	170	850	3	23000	34	503
6.7	65	290	1	22000	21	268
14	130	740	6.2	19000	21	295
8.6	33	300	0	10000	18	242
15	35	240	0.6	12000	22	392
15	60	370	0.7	15000	25	267

a) The data titles coloured in red correspond with sediment data and coloured blue correspond with water column data. The sediment data were collected in a one off sample (i.e. only one value) per pond on 30.04.2013, apart from Idrettsveien where the data were collected on the 11.06.2013. The table has been split into two, so that the values are readable, because when inserting the complete table in landscape, the values were illegible.
b) Age of pond when data were collected last year, in 2013. Also, Skullerund was built in 1999, but was re-sealed with a PEHD membrane in 2001, hence its age is given as 12 not 14.
c) The Chloride data are single values which were collected from the ponds during April 2013.