

**Application of Drone Technology to
Monitoring of the Early-life performance of
Stoneyford Integrated Constructed Wetland**

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ABSTRACT

There is currently a lack of understanding of the design principles and performance monitoring relating to the use of Integrated Constructed Wetlands (ICW) for the treatment of domestic wastewater. This lack of understanding is limiting their development for domestic wastewater treatment in Northern Ireland. The aim of this thesis is to improve the understanding of ICW performance for the treatment of domestic wastewater in Northern Ireland. This thesis achieves the following 6 objectives:

1. Critically review existing knowledge on constructed wetlands, and specifically the use of Integrated Constructed Wetlands for the treatment of domestic wastewater.
2. Determine key variables for assessing Integrated Constructed Wetland performance.
3. Review the design, construction and operation of a full-scale Integrated Constructed Wetland located at Stoneyford to assess its ability to treat domestic wastewater.
4. Design, build and monitor a small-scale research facility at Stoneyford.
5. Offer advice to a revised guidance document for future Integrated Constructed Wetland provision for the treatment of domestic wastewater in Northern Ireland.
6. Investigate the use of drones as a method of monitoring plant performance and identify links to wastewater treatment performance.

This thesis considers the early life performance of Stoneyford Integrated Constructed Wetland in treating domestic wastewater in Northern Ireland. It details issues regarding the design, construction, operation and maintenance of Stoneyford ICW as a full-scale pilot system commissioned by Northern Ireland Water (NIW).

This thesis uses water quality, weather and vegetation performance data from the Stoneyford ICW as a full-scale pilot scheme. Water quality and flow data from a small-scale test rig helps further knowledge and understanding of design principals and wastewater treatment performance monitoring.

Weekly samples were taken manually from each of the 5 ICW ponds and 8 beds of the test rig to monitor water quality over a 19-month period. Results found water quality to improve as it flowed through the 5 ponds of the ICW system. On average, water quality data showed a

reduction of 97% BOD, 86% suspended solids, 90% ammonia and 81.5% COD over the 19-month period. Change in water depth, particularly for pond 1 had a significant detrimental impact on plant growth as illustrated by drone footage taken over a 7-month period. Seasonal differences were found during this period as the ICW and its plant life eco-system is becoming established.

Analysis of the test rig water quality found a shallower depth of 50mm with a larger surface area of 40m²/pe was more effective in the treatment of domestic wastewater, although the differences were marginal at a small scale.

The benefit of using a drone was apparent as it was able to highlight issues relating to plant growth not evident from walking around the ponds. New methods of monitoring plant growth were developed using 2D and 3D image analysis techniques. This allowed for a better understanding of plant performance over time in terms of volume, density and species differentiation.

Stoneyford is the first full-scale ICW for the treatment of domestic wastewater in Northern Ireland. This research concludes that an ICW is a viable alternative to traditional wastewater treatment works in treating domestic sewage in Northern Ireland.

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
BOD	Biological Oxygen Demand
CAST	Co-operative Awards in Science and Technology
CH ₄	Methane
CO ₂	Carbon Dioxide
COD	Chemical Oxygen Demand
CW	Constructed Wetland
DAERA	Department of Environment, Agriculture and Rural Affairs
DARD	Department of Agriculture and Rural Development
DEFRA	Department of Environment, Food and Rural Affairs
DEHLG	Department of Environment, Heritage and Local Government
DEL	Department of Employment and Learning
Ds	Soil Depth
Dw	Water Depth
EMS	Environmental Management System
EPA	Environmental Protection Agency
FWS	Free Water System Constructed Wetland
GHG	Greenhouse Gases
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time

HSSF	Horizontal Sub-Surface Flow Constructed Wetland
ICW	Integrated Constructed Wetland
MRP	Molybdate Reactive Phosphorus
N ₂ O	Nitrous Oxide
NH ₃ -N	Ammoniacal Nitrogen
NI	Northern Ireland
NIEA	Northern Ireland Environment Agency
NISDS	Northern Ireland Sustainable Development Strategy
NIW	Northern Ireland Water
OS	Ordnance Survey
PE	Person Equivalent
PPS	Planning Policy Statement
ROI	Region of Interest
RZM	Root Zone Method
SA	Surface Area
SPA	Settlement Pond A
SPB	Settlement Pond B
SS	Suspended Solids
SSF	Sub-Surface Flow Constructed Wetland
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TR	Test Rig

TSS	Total Suspended Solids
UAV	Unmanned Aviation Vehicle
VSSF	Vertical Sub-Surface Flow Constructed Wetlands
W:L	Width:Length Ratio
WFD	Water Framework Directive (2000/60/EC)
WOC	Water Order Consent
WwTW	Wastewater Treatment Works

NOTE ON ACCESS TO CONTENTS

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CHAPTER 1. INTRODUCTION

1.1 Introduction

This thesis considers the early life performance of Stoneyford Integrated Constructed Wetland (ICW) in treating domestic wastewater in Northern Ireland. It details issues regarding the design, construction, operation and maintenance. The ICW is located close to Stoneyford village, County Antrim. This is the first time an ICW has been used to treat domestic wastewater for a village in Northern Ireland. Stoneyford ICW has therefore been considered by Northern Ireland Water (NIW) as a full-scale trial. This chapter gives background and justification to the research. It defines the thesis title and gives the research questions, aim and objectives.

1.2 Research Background

This research project has been supported through the Department of Employment and Learning (DEL) Co-operative Awards in Science and Technology (CAST) scheme with direct involvement with Northern Ireland Water.

Constructed wetlands are used to treat a range of influents such as dairy farming, abattoirs, industrial effluents, combined sewage and storm-water flows and domestic sewage (Scholz, M., et al., 2007a; 2007b). This thesis considers a specific type known as an Integrated Constructed Wetland (ICW) as a sustainable alternative to the traditional domestic wastewater treatment works for the treatment of domestic wastewater. Figure 1.1 illustrates an aerial image of Stoneyford ICW.

An ICW is an engineered system specifically designed to simulate the bio-filtration processes of a natural system to remediate contaminated wastewater and mitigate the pollution of nearby water bodies. This is done using strategically chosen aquatic plants, suited to the specific site, which filter and remove contaminants from the water as it flows through the ponds of the constructed wetland. They are designed to work as an integrated ecosystem, combining the functions of the natural environment with human activities (Moshiri, G. A, 1993). In other words, they are a natural means of treating wastewater in a controlled and manageable method (Vymazal, J., 2011).



Figure 1.1 Aerial image of Stoneyford ICW.

1.3 Research Justification

The treatment of sewage in a traditional wastewater treatment works is typically capital and energy intensive. It is not sustainable in the long term. Sustainability was included within the Water Framework Directive 2000/60/EC (European Parliament, 2000) and water protection is integrated into EU sustainable development strategies (Northern Ireland Executive, 2010).

These legislative requirements coupled with global pressures to develop sustainably have created a need in the water treatment industry to combine environmental protection with innovative engineering techniques. The use of an ICW is now regarded by NIW as a sustainable alternative to traditional wastewater treatment works and prompted the full-scale development at Stoneyford.

There is currently a lack of understanding of the design principles and performance monitoring relating to the use of ICW's for the treatment of domestic wastewater. This research uses data from the full-scale pilot scheme and a small-scale test rig to further knowledge and understanding of design principles and wastewater treatment performance monitoring. The use of a drone was investigated to determine its suitability in monitoring plant performance within the ICW. The findings of this thesis will aid the decision making process of future ICW provision in Northern Ireland.

1.4 Research Questions, Aim and Objectives

This thesis considers the following research questions:

1. What are the significant variables that impact the treatment performance of an ICW for domestic wastewater?
2. Can the design of an ICW be improved to optimise the performance of domestic wastewater treatment?
3. What is the relationship between plants and wastewater treatment?
4. Is an ICW effected by environmental, ecological and seasonal factors?
5. Can the performance of plant growth be better monitored?
6. Are ICWs a viable alternative to traditional wastewater treatment works in treating domestic sewage in Northern Ireland?

The thesis has the following aim:

Improve the understanding of ICW performance for the treatment of domestic wastewater in Northern Ireland.

The thesis has the following objectives:

1. Critically review existing knowledge on constructed wetlands, and specifically the use of Integrated Constructed Wetlands for the treatment of domestic wastewater.
2. Determine key variables for assessing Integrated Constructed Wetland performance.

3. Review the design, construction and operation of a full-scale Integrated Constructed Wetland located at Stoneyford to assess its ability to treat domestic wastewater.
4. Design, build and monitor a small-scale research facility at Stoneyford.
5. Offer advice to a revised guidance document for future Integrated Constructed Wetland provision for the treatment of domestic wastewater in Northern Ireland.
6. Investigate the use of drones as a method of monitoring plant performance and identify links to wastewater treatment performance.

1.5 Thesis Structure

The thesis has the following structure:

➤ **Chapter 1 Introduction:**

This chapter introduces the thesis by providing a background to the research and highlighting the aim and objectives of the study.

➤ **Chapter 2 Literature Review Background, Design and Performance of Constructed Wetlands:**

This chapter provides a critical review of literature identifying knowledge gaps. The chapter considers the different types of constructed wetland and their applications. The review then focuses on the performance of Integrated Constructed Wetlands and Horizontal Sub-Surface Flow wetlands in treating wastewater from various sources and the variables that may impact this performance. The literature review also discusses the contexts in which constructed wetlands are appraised, other than their ability to treat wastewater. Finally, the literature review details the current guidance available for ICWs in wastewater treatment within Northern Ireland.

➤ **Chapter 3 Stoneyford ICW and Test Rig Development:**

This chapter details the design and construction processes involved in the building of Stoneyford ICW and Test Rig. It gives information regarding the planning process, the details of design and the stages involved in the ICW construction, operation and maintenance. This chapter also details the design and justification for the development of a small-scale test rig for the investigation of design parameters of water depth and surface area.

➤ **Chapter 4 Methods:**

This chapter describes and explains the methods used in the 4 main studies included within this thesis. The studies involved include stakeholder engagement, a full-scale Integrated Constructed Wetland at Stoneyford, a small-scale test rig within Stoneyford ICW, and the use of a drone to measure and monitor plant performance at Stoneyford ICW.

➤ **Chapter 5 Results:**

This chapter provides the results of the 4 main studies included within this thesis. The chapter provides analysis and discussion from the stakeholder engagement as well as analysis of data from the full-scale ICW and small-scale test rig at Stoneyford. The chapter also provides an analysis of data from aerial imagery captured by a drone to monitor ICW plant performance.

➤ **Chapter 6 Discussion:**

This chapter discusses the results of the research in relation to each of the research objectives. The chapter provides a summary of the key findings and their comparison to previous research.

➤ **Chapter 7 Conclusions:**

This chapter concludes the thesis by highlighting key findings and responding to the points made within the research questions.

➤ **Chapter 8 Future Recommendations:**

This chapter identifies the need for further research and highlights recommended topics of focus.

➤ **References**

➤ **Bibliography**

➤ **Appendices**

CHAPTER 2. LITERATURE REVIEW BACKGROUND, DESIGN AND PERFORMANCE OF CONSTRUCTED WETLANDS

2.1 Introduction

This chapter reviews the treatment of domestic wastewater in Northern Ireland and identifies the need for more sustainable alternatives. The literature review provides a background to the design and performance of constructed wetlands. It considers the performance and analysis of Integrated Constructed Wetlands and Horizontal Sub-Surface Flow systems. This chapter provides a critical review of current guidance documents used for the implementation of ICWs. This chapter concludes with a summary of findings and identification of knowledge gaps for further research.

2.2 The Need to Treat Domestic Sewage

Sewage is defined as 'waste water and excrement conveyed in sewers' and is 'generally a mixture of domestic waste water from baths, sinks, washing machines and toilets, waste water from industry and rainwater run-off from roads and other surfaced areas' (DEFRA, 2002). Sewage can be a mixture of water which has been used for a variety of purposes in the home, at work or in leisure activities, rainwater from roads, footpaths and roofs and water used for business and industrial purposes' (NIW, 2016a). Sewage contains organic matter, bacteria, chemicals and other detritus but the naturally occurring bacteria eventually breaks the most of sewage down as the microorganisms feed on the organic matter and release gases into the atmosphere through biological and chemical processes, while the rest remains retained (Heritage, J., et al., 1999). However, this process uses oxygen dissolved in the water which can cause further problems for plants and animals within and around the waterway.

Sewage treatment works are an engineering system used to clean sewage and remove objects or organisms that have the potential to harm the environment. They attempt to reproduce what would naturally occur in the environment, by settling out the solid matter and then using bacteria to digest and break down the organic substances in a controlled manner. This is referred to as Primary and Secondary Treatment. Sometimes a third Tertiary level of treatment is required which involves the disinfection of secondary effluent to protect sensitive waters such as bathing or shellfish waters. It may also involve removing nutrients from the water to mitigate the effects of eutrophication. Eutrophication is defined by DEFRA as '*the process where excessive nutrients, especially nitrogen and/or phosphorus compounds, cause an accelerated growth of algae and higher forms of plant life....which causes an undesirable*

disturbance to the balance of organisms present in the water and to the quality of the water concerned' (DEFRA, 2002).

Allowing sewage to build up or flow directly into natural water bodies can cause various types of detrimental consequences for the environment and its ecology by contaminating water ways and spreading disease NIW, (2016a); DAERA-NI (2016a); Burnett-Hall, (2012).

2.3 Sewage Discharge Regulation in Northern Ireland

Due to its adverse impact on social and environmental communities, it is an offence to discharge sewage into any waterbody other than a designated foul sewer. There are numerous legislations that regulate the control, treatment and discharge of wastewater in Northern Ireland. The European Water Framework Directive 2000/60/EC (WFD) is the most integrated. When introduced in 2000, the aim of the WFD was to '*achieve good surface water status, good ecological potential, and good groundwater status in all waters by the end of 2015*'. The WFD has since been the main driver for the implementation of sustainable wastewater treatment infrastructure in Europe (Burnett-Hall, 2012).

The Water Utility Regulation Group regulates discharges made by the Water Utility Sector in Northern Ireland. Northern Ireland Water (NIW) is responsible for discharges from all wastewater treatment works under the Water (Northern Ireland) Order 1999. Consent is only given to the discharge of water that meets the required quality and quantity of the discharge into the water environment. The consent standard for a treatment works normally consists of a requirement for Biological Oxygen Demand (BOD), suspended solids, pH, iron, total available chlorine and ammonia. Sometimes consent standards are given for nutrients such as nitrates, nitrites, total nitrogen and phosphorus (DAERA-NI, 2016a).

2.4 Technologies used in Sewage Treatment

The domestic sewerage system is typically a network of pipes, pumps and sewers that collect and carry sewage away from source to be cleaned and disposed. There are two main types of sewerage system used in Northern Ireland as described in Table 2.1. The sewage system carries the combined and foul sewage to the wastewater treatment works where it undergoes

six stages of treatment (Table 2.2) before being safely disposed in accordance with legal requirements as set by the Northern Ireland Environmental Agency (NIEA). Clean water typically goes to a nearby watercourse and sludge is disposed either by incineration or landfill (NIW (2016a); NI Direct (2016)):

Table 2.1 Types of Sewage System used in Northern Ireland (NIW, 2016a).

Type of sewage system	Operation
Combined sewers	Carries both sewage and rainwater in a single pipe.
Separate sewers	Uses two pipes. One takes foul sewage to a sewage treatment works and the second carries rainwater (storm sewage) straight to a nearby stream or river, as rainwater does not require treatment.

Table 2.2 Six Stages of Treatment (NIW, 2016a).

Stage	Purpose
Preliminary:	Removes large debris, sand and grit.
First settlement:	Removes the small solids.
Biological phase:	Removes things that are dissolved.
Second settlement:	Removes dead bacteria and their waste.
Tertiary treatment:	Removes any harmful germs.
Sludge drying:	Removes water so that it can be recycled as a fertilizer or a fuel.

2.5 The Need for More Sustainable Sewage Treatment Methods

The treatment of sewage in a traditional wastewater treatment works (WwTW) is typically capital and energy intensive which is not sustainable in the long term. The Northern Ireland Sustainable Development Strategy proposed *‘to provide, maintain and regulate the infrastructure necessary to deliver high quality water and sewerage services and acceptable levels of compliance with EU and other relevant standards’* (Northern Ireland Executive, 2010).

The 2015 *Report on the progress in implementation of the Water Framework Directive Programmes of Measures* details the European Commission’s recommendations for member

states in order to improve their success in achieving the WFD objective. One recommendation made to the UK, which includes Northern Ireland, is as follows:

‘Consider and prioritise the use of green infrastructure and/or natural water retention measures that provide a range of environmental (improvements in water quality, increase water infiltration and thus aquifer recharge, flood protection, habitat conservation etc.), social and economic benefits which can be in many cases more cost-effective than grey infrastructure’ (Northern Ireland Executive, 2010).

These legislative requirements coupled with global pressures to develop more sustainable solutions have created a need in the water treatment industry to combine environmental protection with innovative engineering techniques. This has offered scope for developers and businesses to work responsibly whilst complying with these suitability legislative requirements (Pandey, G., 2001). Numerous engineering techniques are now available to remediate and prevent water pollution, for example, the full scale ICW development at Stoneyford by NIW.

2.6 Constructed Wetlands

Constructed wetlands are engineered systems designed to simulate the bio-filtration processes of a natural system to remediate contaminated wastewater and mitigate the pollution of nearby water bodies. This is done by using specific plants suited to the site which filter and remove contaminants from the water as it flows through the engineered system.

Constructed wetlands are designed to work as an integrated ecosystem, combining the functions of the natural environment with human activities, to help enhance overall water quality (Moshiri, G. A, 1993). They are a natural means of treating wastewater, but through a controlled and manageable method (Vymazal, J., 2011).

Constructed wetlands have proven to be effective in the removal of contaminants from wastewaters and differing types allow this method of wastewater treatment to be versatile. Table 2.3 highlights and compares the main differences between constructed wetland types.

Table 2.3 Summary of constructed wetland design.

Variables	FWS	HSSF	VSSF	Hybrid	ICW
Soil Depth	>15mm	>300mm	>500mm	Various	150mm
Water Depth	>285mm	<200mm	<250mm	<300mm	<300mm
Plant Type	Emergent and/or Floating	Emergent	Emergent	Various	Emergent
Surface Area	20-40m ² /pe	5-10m ² /pe	1-3m ² /pe	3-10m ² /pe	20-40m ² /pe
No. Ponds	1+	2-5	2-5	Various	>4
Application	Tertiary treatment of stormwater and municipal wastewater	Municipal, domestic, industrial, food- processing, agriculture, landfill.	Landfill, domestic, municipal.	Municipal, domestic, industrial, food- processing, agriculture, landfill	Municipal, domestic, industrial, food- processing, agriculture, landfill
Advantages	Natural design, low maintenance.	Small surface area, high flow capacity, low risk of human exposure.	Low surface area, high concentration treatments, low risk of human exposure.	Low surface area, variable applications, high treatment performance.	Integrated design, social inclusion/ leisure facility, low maintenance required.
Disadvantages	Risk of human exposure to pathogens, large surface area.	High maintenance/ operational costs.	High maintenance/ operational costs, risk of clogging.	High maintenance/ operational costs	Large surface area, risk of human exposure to pathogens.

The constructed wetland principle has been applied to the treatment of a range of influents (Scholz, M., et al., 2007). They normally take the form of a number of ponds where influent is pumped, or passed by gravity through channels into each of the ponds sequentially to be treated. As the polluting influent flows through the ponds, it is subjected to a number of integrated processes such as sedimentation, filtration, nitrification, denitrification, sorption and plant uptake until it exits (Figure 2.1). Each pond has its own function depending on the level of contaminants. Generally, the first pond deals with heavier solids' sedimentation whereas the final pond may render the water suitable for discharge into a nearby water body or watercourse.

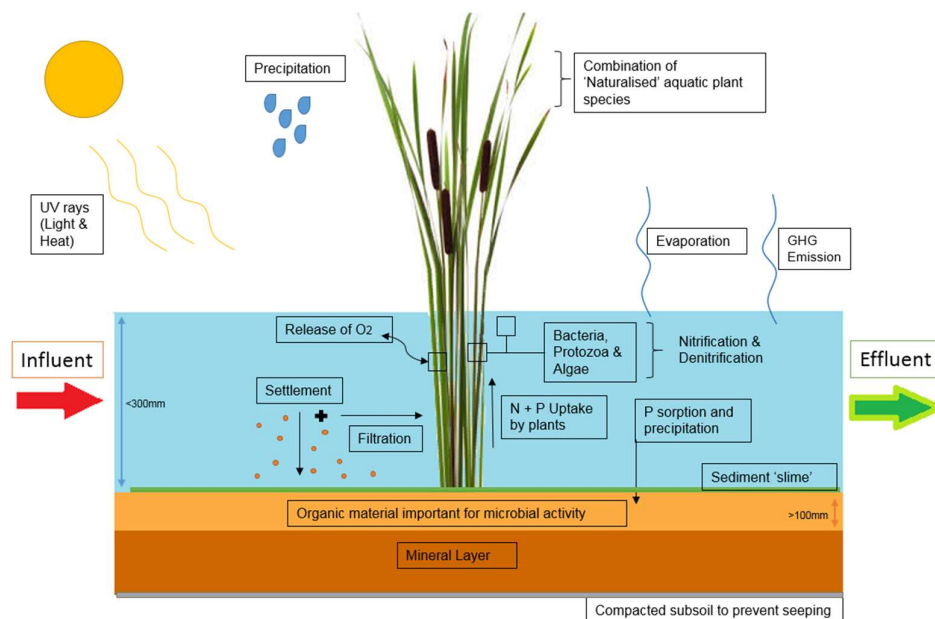


Figure 2.1 Processes of wastewater treatment within a constructed wetland.

2.6.1 Free Water Surface Flow Constructed Wetlands

Free Water Surface Flow Constructed Wetlands (FWS) are systems which contain areas of open water planted with emergent and/or floating aquatic species (Kadlec, R.H, et al., 2008). They are typically designed with a water depth of 285 to 300mm and a shallow media depth for plant rooting. A FWS schematic is shown in Figure 2.2. The water area is the main

treatment zone capable of treating around 30mm/d of wastewater (Kadlec, R. H., 2009). As the wastewater enters through an inlet, it flows freely within the pond where it is subjected to various physical, chemical and biological treatment processes.

The FWS is an effective means of treating wastewater for the removal of organics and suspended solids due to presence of microbial processes and the filtration capabilities of the plants. They are commonly used as a tertiary treatment system for the treatment of storm water or municipal wastewater (Vymazal, J. 2011). Due to a risk of human exposure to untreated pathogens, FWS are not commonly used for the treatment of secondary wastewater (Kadlec, R.H., et al., 2008). Although FWS are of similar appearance to natural wetlands, their higher land requirement coupled with lower hydraulic efficiencies have resulted in them being less preferable to Sub-Surface Flow Systems (Kadlec, R.H., 2009).

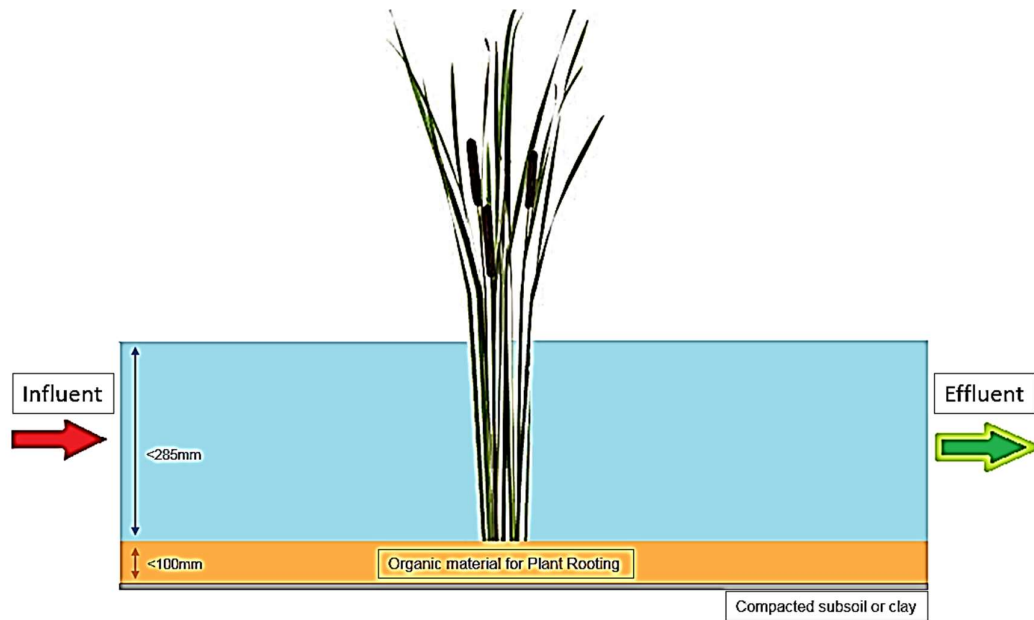


Figure 2.2 Free Water Surface constructed wetland cross section.

2.6.2 Sub-Surface Flow Constructed Wetlands

Sub-Surface Flow Constructed Wetlands (SSF) are systems which treat the influent as it passes through growth media below the surface of the wetland. This concept originated in Germany in the 1970's (Brix H., (1987); Moshiri, G. A., (1993)) as the 'Root Zone Method' (RZM). Studies by Kickuth (1977) tested the treatment of municipal wastewater using soil, based on

knowledge from sewage farming practices in the UK (Kadlec, R. H., et al., 2008). Successful treatments of Biological Oxygen Demand (BOD), Total Nitrogen (N) and Total Phosphorus (P) meant that the RZM was a feasible substitute to traditional WwTW. Since then, the use of SSFs has become increasingly popular across Europe and the world for the treatment of various wastewaters (Brix. H., 1987).

The design of a SSF typically consists of an impermeable bed overlain with soil, sand and/or gravel. This is planted with emergent macrophytes which treat the wastewater as it flows horizontally or vertically through the rhizosphere of the plant root zone (Moshiri, G.A, (1993); Kadlec, R.H., et al., (2008)). Unlike the FWS, exposure to untreated wastewater and subsequent health risks are improbable in a SSF. As a result, they are more likely to be used for the treatment of secondary wastewater (Kadlec, R. H., et al., 2008).

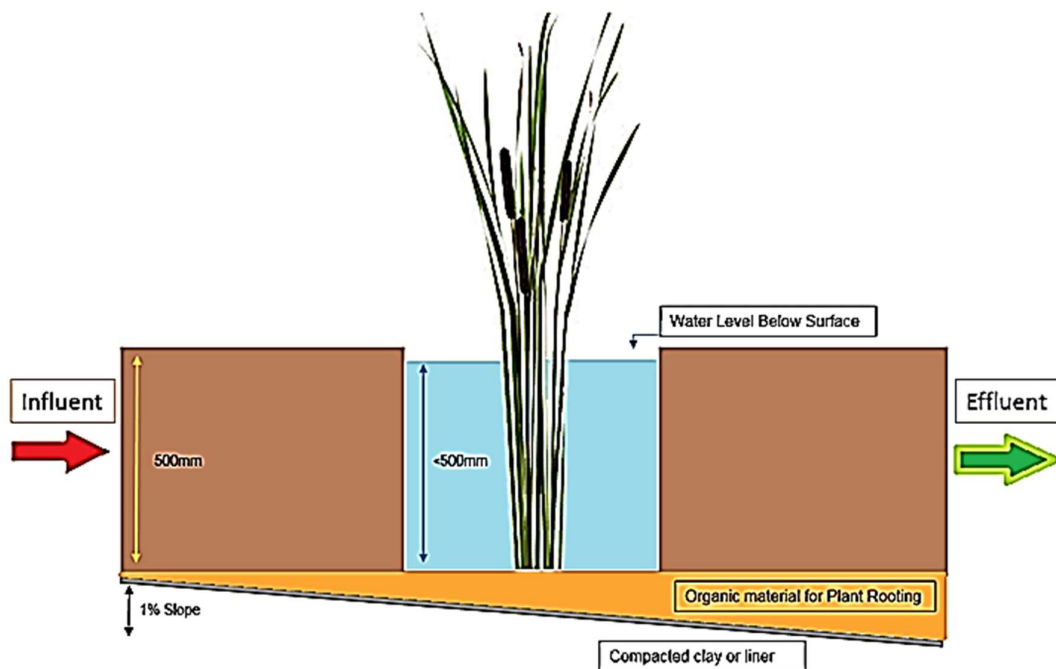


Figure 2.3. Horizontal Sub-Surface Flow constructed wetland cross section.

2.6.3 Horizontal Sub-Surface Flow Constructed Wetlands

Horizontal Sub-Surface Flow (HSSF) Constructed Wetlands describe a system where influent is pumped or passed through an inlet into a shallow pond planted with emergent aquatic plant species. From here, it gradually flows horizontally across the area of the pond where it is subjected to a number of treatment processes and biochemical conditions.

As shown in Figure 2.3, the HSSF system is typically designed to flow downwards across a slight gradient of around 1% (US EPA, 1988). They have a shallow bed depth of around 500mm where at least 60% of the volume is occupied by soil and gravel (Kadlec, R. H., 2009). The higher ratio of plant media to water depth makes it more difficult for the influent to flow freely through the pond. This subjects the influent to various barriers which filter and treat it. This increase in barriers results in the improved treatment capacity of the HSSF wetland of approximately 70mm/d. This is more than twice that of a FWS despite it having a lower Hydraulic Retention Time (HRT) of approximately three times less (Kadlec, R. H., 2009).

HSSF systems have higher maintenance costs than FWS (Kadlec, R. H., et al., 2008). They require much less land take than FWS with median size range of 100 times smaller (Kadlec, R. H., 2009) and are considered a more efficient system. However, FWS are preferred for the treatment of certain types of influent with a high contaminant concentration (Kadlec, R. H., 2009). HSSFs were originally designed for the treatment of municipal and domestic wastewater. However, research has shown that they are successful in the treatment of wastewater from industry, food-processing, agriculture, various runoff waters, and landfill leachate (Vymazal, J., 2007; 2009).

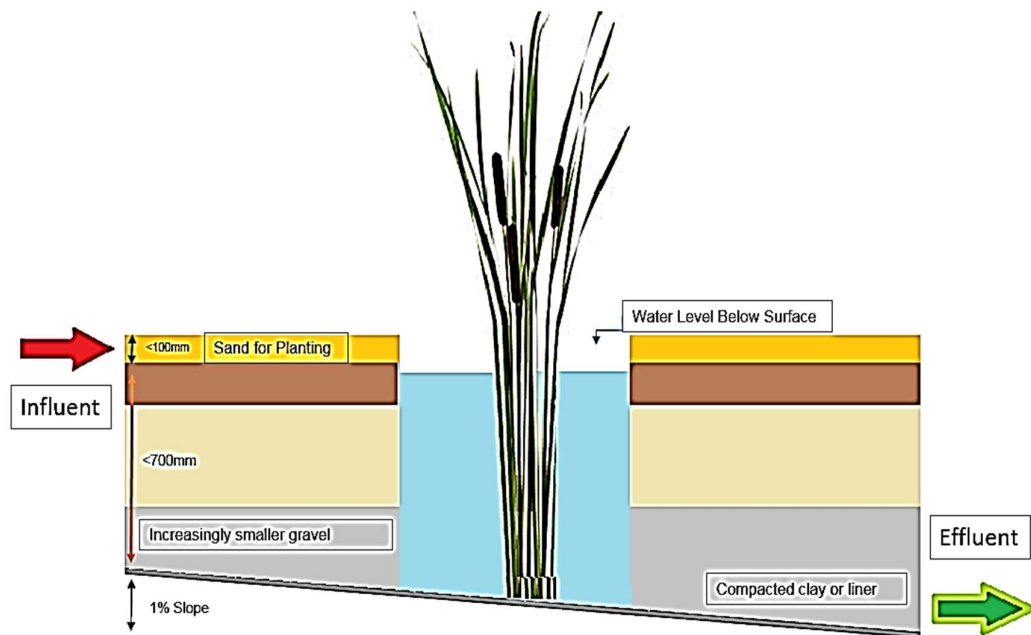


Figure 2.4. Vertical Sub-Surface Flow constructed wetland cross section.

2.6.4 Vertical Sub-Surface Flow Constructed Wetlands

Vertical Sub-Surface Flow (VSSF) Constructed Wetlands are similar to HSSFs in that the wastewater is pumped or passed through a pond planted with emergent plant species. As shown in Figure 2.4 the influent is encouraged to flow vertically through a growth media of soil, sand or gravel, as opposed to horizontally. Unlike HSSFs which have a continuous flow of wastewater through the system, VSSFs are fed wastewater intermittently through batch loads.

This method of loading results in the pond being flooded, encouraging wastewater to filtrate vertically through the sand and gravel in an upward or downward motion. As the wastewater filters through the growth media it is subject to a number of treatment processes before being drained off at the bottom (surface inlet) or on the surface (bottom inlet) (Kadlec, R. H., et al., (2008); Vymazal, J., (2011)).

Flooding the pond using intermittent flow gives the pond time to completely drain between loads which allows the sand and gravel to aerate, providing good conditions for nitrification (Cooper, P. F., et al., (1996); Moshiri, G. A., (1993)). However, this reduces the system's ability to denitrify the contaminant and allow gaseous nitrogen to escape into the atmosphere (Vymazal, J., 2011). VSSFs are typically designed as a near flat bed (approximately 1% slope) laid with a bottom layer of gravel, with a diameter of between 30-60mm. This layer is topped with increasingly smaller diameters of gravel until a layer of sand (approximately 80-100mm deep) is reached on the surface of the pond suitable for planting the emergent species.

The total depth of the VSSF pond is around 800mm including around 500mm of media depth and a maximum of 250mm water depth (Cooper, P. F., et al., (1996); Kadlec, R. H., et al., (2008)). VSSFs have a land requirement of 1-3m²/pe which is much less than that of the HSSF at 5-10m²/PE (Kadlec, R. H., et al., 2008).

VSSFs are known for their ability to oxidise ammonia and subsequently they are typically used for the treatment of landfill leachate and high concentrations of domestic and municipal wastewater. However, their poor ability to deal with suspended solids due to clogging (Cooper, P., 1999) coupled with the higher operation and maintenance costs (Kadlec, R. H., et al., 2008) has meant that VSSF systems are not as widely used as the HSSF systems (Vymazal, J., 2005).

2.6.5 Hybrid Constructed Wetland Systems

Both HSSF and VSSF systems have their weaknesses by way of treatment capacities or efficiency (Cooper, P., (1999); Vymazal, J., (2007)). HSSF systems are good for the removal of suspended solids due to their efficient hydraulic retention, the reduction of BOD due to the release of oxygen from biological processes, and the treatment of ammonia through denitrification. However, HSSF are poor performers of nitrification due to a limited oxygen transfer capability as much of the oxygen is used during the denitrification process. As a result, HSSF systems are not effective in releasing the nitrogen from ammonia into the atmosphere.

VSSF systems are good for the nitrification process due to the high oxygen transfer when the system becomes aerated. This allows them to be effective in the reduction of BOD and COD. Unfortunately, as they are not effective in treating suspended solids they are susceptible to clogging (); Cooper, P., et al., (1996); Cooper, P., (1999); Vymazal, J., (2007)).

This led to development of hybrid constructed wetland systems to increase the efficiency of wastewater treatment (Vymazal, J., 2011). Hybrid systems were derived from the original Max Planck Institute Process (MPIP) systems of Dr Kathe Seidel in the early 1960s which combined a series of VSSF and HSSF filter beds to test treatment performance of aquatic plants (Kadlec, R. H., et al.,(2008); Vymazal, J., (2011)).

Seidel focused her studies on the RZM of HSSF systems, which became the most commonly used system of that time (Kadlec, R. H., et al., 2008). Hybrid systems were further developed in Poland, France and the UK (Kadlec, R. H., et al., (2008); Cooper, P., (1999)). There are two main types of hybrid systems, based on whether it starts with a VSSF or HSSF system (Cooper, P., 1999) as seen in Figure 2.5.

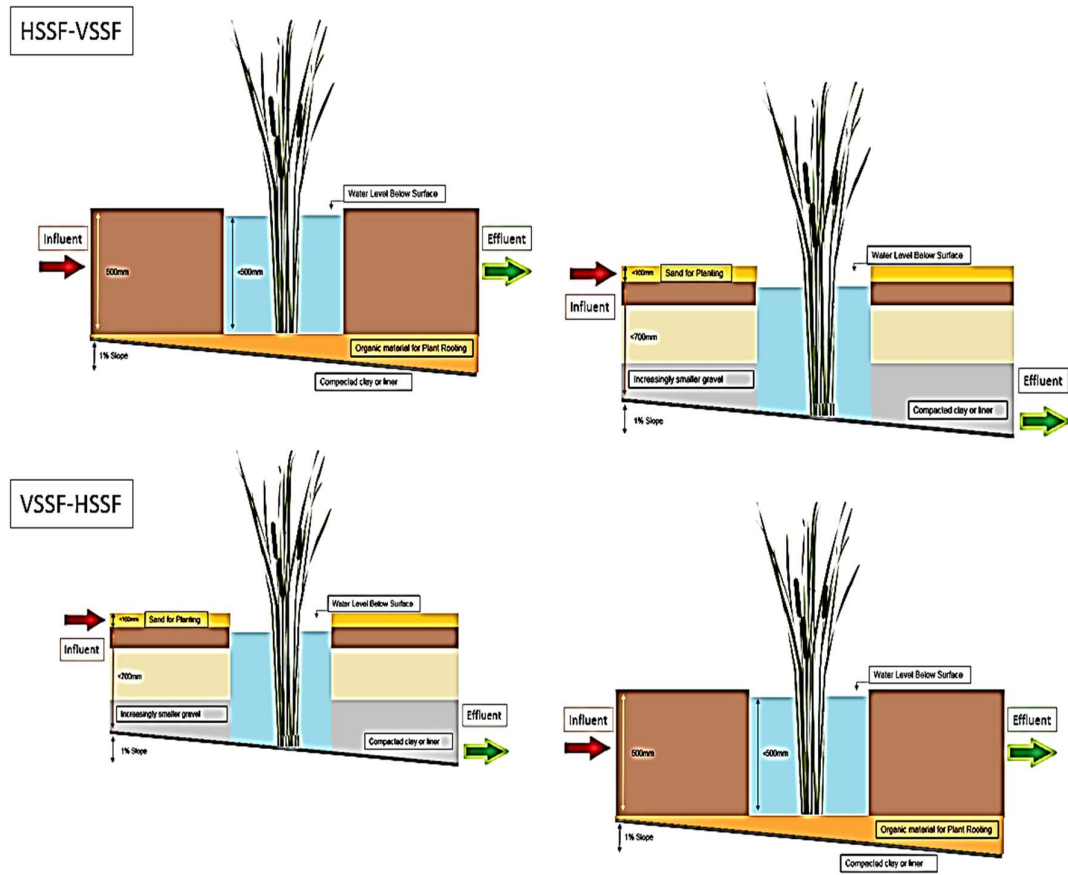


Figure 2.5 Hybrid constructed wetlands cross sections.

2.7 Integrated Constructed Wetlands (ICW)

Integrated Constructed Wetlands (ICW) are a relatively new addition to the constructed wetland concept with their origins in Ireland attributed to Rory Harrington in the 1990s. The concept was originally developed to enhance the environmental management of the Dunnhill - Annestown stream in County Waterford, Ireland (Figure 2.6) which was heavily polluted due to farmyard run-off (Scholz, M., et al., (2007); Harrington, R., et al., (2005)).

The ICW design is based on the concept of FWS wetlands in that water flows freely by gravity above the surface of the soil (Harrington, R., and Ryder, C., 2002). However, ICWs differ from FWS wetlands in that they are an integrated method of managing the natural resources of both the land and water (Harrington, R., and Ryder, C., (2002); Dunne, E., et al., (2005)).



Figure 2.6 Location of Dunhill, County Waterford, Ireland (Google Maps, 2017).

ICWs use a holistic approach to integrating the concept of constructed wetlands into the local landscape, soils, topography, and biodiversity. This creates a sustainable and viable wastewater treatment system which mimics the processes and developments of a natural wetland (Scholz, M., et al., 2007).

ICWs were originally intended for treating farmyard dirty water and its associated high phosphorus concentrations. As such, the sizing and design of the ICW system was focused primarily on this basis (Carty, A., et al., (2008); Scholz, M., et al., (2007)). It has been recommended that the ICW wetland area is at least 1.3 times the farmyard area, separated into at least 4 pond cells with a width: length aspect ratio of 1:2.2 (Carty, A., et al., (2008); Scholz, M., et al.,(2007)).

Although ICWs are based on the concept of FWS wetlands which require a minimum of 285mm water depth, ICWs are designed to have a maximum water depth of 300mm, with a recommended minimum of 100-200mm (Carty, A., et al., 2008). Despite this shallower depth,

an ICW incorporates the same land area requirement typically used by an FWS at 20-40m²/PE (US Environmental Protection Agency, 1988).

The performance of ICWs in treating farm yard wastewater has been successful with removal rates of 95% Molybdate Reactive Phosphorus (MRP) and 98% ammonium-N claimed by Harrington, R. and McInnes, R., (2009). They have been trialled in Ireland for treating domestic wastewater and have achieved an average of 91.4% of Total Phosphorus and 90.1% MRP from secondary wastewater (Dzakpasu, M., et al., 2014).

Due to the high performance of an ICW and their ability to integrate sustainably into the local landscape they are regarded as a viable alternative to conventional constructed treatment wetlands (Scholz, M., et al., 2007). However, like FWS wetlands, issues regarding their land take and the associated capital costs have prevented ICWs from becoming as common as their smaller SSF counterparts.

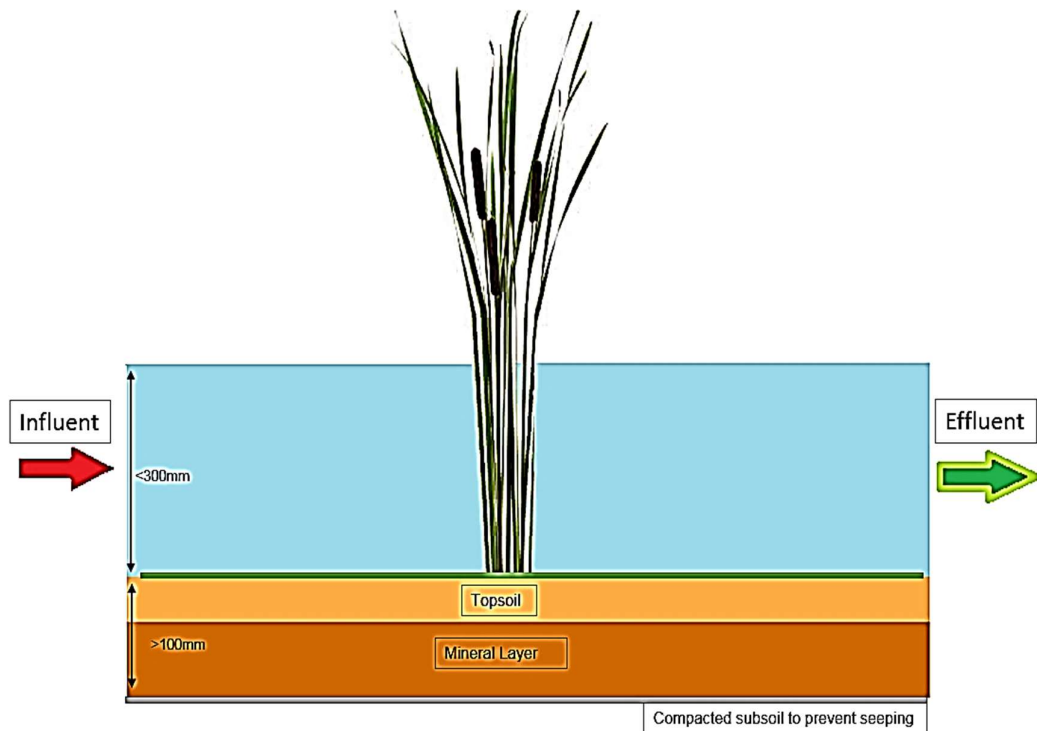


Figure 2.7. Integrated Constructed Wetlands cross section.

2.8 Comparison of HSSF and ICW

The use of a particular type of constructed wetland design is specific to the needs and expectations of the developer. Continuous improvements of wetland performance across all types of treatment wetlands means it could be possible to implement any one of the systems to get a desired result. For the purpose of this thesis the scope of research will be limited to the performance and analysis of Horizontal Sub-Surface Flow constructed wetlands and Integrated Constructed Wetlands. The reason for this scope is due to a number of points:

- HSSF wetlands were originally designed for the treatment of municipal and domestic wastewater (Vymazal, J., 2007; 2009) and so are well renowned for their effectiveness and efficiency at doing so. Their high performance rate coupled with a low surface area and hydraulic retention time would deem HSSF systems more favourable, and thus more common for the treatment of domestic wastewater over ICWs. Therefore, it is suggested that further investigation of these systems will aid in developing an appreciation of their efficiency. It will enhance understanding of how performance of ICWs can be improved and become an alternative to traditional wastewater treatment systems.
- ICWs are more widely used for the treatment of highly contaminated wastewater such as animal or industrial waste (Kadlec, R, H., 2009). However, in more recent years, the use of ICWs for the treatment of domestic and municipal waste is becoming more popular due to their low operational and maintenance costs and their ability to integrate wholly into the environment. Northern Ireland Water (NIW) has recently implemented the first ICW in the UK for the treatment of domestic and municipal waste at Stoneyford. It is hoped that this wetland proves to be an effective and sustainable alternative to traditional wastewater treatment works for NIW and they have invested considerable amounts in providing substantial apparatus for the collection, measurement and monitoring of treatment performance. Thus, it would be extensively advantageous to avail of this information in order to appraise the performance of a full scale ICW for the treatment of domestic wastewater, in comparison to other available wetland designs.

HSSF and ICW wetlands have differences in their design, use and treatment capacities. A summary highlighting these differences can be found in Table 2.4. The vegetation type and

amount within these two wetland systems are very similar in that they are both planted with emergent species which are suited to the climate and conditions of the local area (Carty, A., et al., (2008); Ellis, J. B., et al., (2003)).

Table 2.4 HSSF and ICW design summary.

Feature	HSSF	ICW
Surface Area	3-5m ² /pe or 5-10m ² /pe	5-10m ² /pe or 20-40m ² /pe
Shape	Uniform / Rectangular	Irregular / Curved
Water Depth	Below Surface	50-300mm above surface
Media Type	Soil, Sand, Silt and Gravel	Soil
Media Depth	300-500mm	<200mm
Liner	Artificial or clay	Clay

There are a number of different species which are suitable for use in treatment wetlands. The more commonly used species within HSSF wetlands are *Phragmites australis* (Common Reed), *Typha latifolia* (Reedmace), *Schoenoplectus* spp. (Bulrush) and *Carex* spp. (Sedges) (Ellis, J. B., et al., 2003).

ICWs are also known to be planted with these species. They are more commonly planted with *Carex riparia* (Greater Pond Sedge), *Glyceria maxima* (Reed Sweet Grass) and *Typha latifolia* (Reedmace) (Carty, A., et al., 2008).

HSSF wetlands were originally designed for the treatment of municipal and domestic wastewater. Research has shown that they are also successful in treating higher contaminated wastewaters from industry, agriculture, run-off and landfill leachates (Vymazal, J., 2007; 2009).

ICWs however were originally designed for the treatment of agricultural wastewater (Carty, A., et al., (2008); Scholz, M., et al., (2007)) but have since proven to be very effective in treating other wastewaters from industry, food processing and domestic sewage (Dzakpasu, M., et al., 2014).

2.9 Comparisons of Treatment Performance of HSSF and ICW

HSSF and ICW systems are generally implemented depending on the various type of wastewater being treated. However, they are both capable of treating a number of different contaminants to varying degrees. Each of these contaminants is now discussed.

2.9.1 Treating Ammonium

Ammonium-N can be toxic to many plants so a high concentration of this within wastewater will cause problems for the macrophytes planted within the constructed wetlands and prevent optimum performance (Britto, J. D., and Kronzucker, H. J., (2002); Harrington, A., (2005)). Despite this, constructed wetlands have proven to be very effective in the removal of ammonium from various concentrations of wastewaters.

For example, a lab study on the effectiveness of constructed wetlands for the tertiary treatment of petroleum refinery effluent found that average ammonia (measured as Ammoniacal Nitrogen ($\text{NH}_3\text{-N}$)) removal was as much as 95% and overall toxicity of the wastewater was also reduced, suggesting that wetlands are effective even at high toxicity levels (Huddleston, G. M, et al., 2000).

Although this was not a full-scale representation of a constructed wetland, and was based on the tertiary treatment of effluent, it suggests the potential that treatment wetlands have in removing ammonia from highly toxic sources.

HSSF CW have also shown positive results in managing urban lake water quality with around 53.8% removal of $\text{NH}_3\text{-N}$ (Cui, F., et al., 2011). However, much higher performances for ammonium removal can be seen for ICWs. A study at Glaslough tested the performance of an ICW at treating domestic wastewater and found an average $\text{NH}_3\text{-N}$ removal of 98% over a period of 2 years (Dzakpasu, M., et al., 2011). A similar study by Harrington, C., et al., (2012) found a mass removal of 98.1%-99.9% ammonia-nitrogen over an 18-month period in a wetland treating digested separated swine wastewater.

ICWs have been known to continue in effectiveness as the system matures, unlike other wetland systems. For example, a study of a 15 pond ICW system in Annesvalley Catchment in Ireland tested the long term performance of wetlands in treating wastewater. The study found

that the removal of ammonia-nitrate remained high at an average of 99.6% and showed no signs of decreasing with wetland maturity. There were, however, variations in removal efficiencies between seasons with spring and summer (99.4% and 99.7%) having a higher efficiency than autumn and winter (98.7% and 99.3%) although these were not significant as shown in Table 2.5 (Mustafa, A., et al., 2009).

Table 2.5 Seasonal comparison of nutrient concentrations – Table 3 (Mustafa, A., et al., 2009).

Table 3 – Seasonal comparison of nutrient concentrations based on 46 annual data points for the integrated constructed wetland treating farmyard runoff in 2005.				
Nutrient	Spring	Summer	Autumn	Winter
Ammonia-nitrogen (mean \pm standard deviation)				
Influent (mg/l)	28.09 \pm 21.389*	50.99 \pm 56.640*	72.09 \pm 62.597*	38.15 \pm 22.960*
Effluent (mg/l)	0.17 \pm 0.286*	0.16 \pm 0.201**	0.92 \pm 0.769***	0.24 \pm 0.197*
RE (%)	99.4	99.7	98.7	99.3
Molybdate reactive phosphorus (mean \pm standard deviation)				
Influent (mg/l)	12.23 \pm 11.654*	10.54 \pm 6.430*	21.62 \pm 13.113*	15.08 \pm 6.555*
Effluent (mg/l)	0.52 \pm 0.235*	0.98 \pm 0.147 [‡]	1.09 \pm 0.511 [†]	1.02 \pm 1.503*
RE (%)	95.7	90.7	94.9	93.2
RE, removal efficiency; means followed by the same symbols are not statistically significantly different ($p < 0.05$).				

Dong, Y., et al., (2013) tested the impact of hydraulic loading and seasonal variations of ammonia-nitrogen removal within a constructed wetland and found seasonal variations in performance. However, this was due to significant flooding during the test period which increased the HLR and an overall average removal efficiency of 91.7% was still achieved (Dong, Y., et al., 2013).

Overall, it can be concluded that ICWs can achieve higher ammonium removal rates than HSSF, even when shock loadings were introduced, or as the wetland matures. However, HSSF wetlands are still capable of treating ammonium contaminated wastewaters and could still be the better option for treating influent with lower ammonium concentrations.

2.9.2 Treating Nitrogen

Constructed wetlands have proven effective in removing 95.8% of Total Nitrogen (TN) from eutrophic water even under high concentrations and shock loading (Shui, Y. et al., 2011). HSSFs have again, showed how they are effective with a total nitrogen removal of 47.9% in Xing-qing Lake in Xi'an City (Cui, F., et al., 2011).

Another study tested the performance of HSSF wetlands using three different substrates (alum sludge, gravel or zeolite) at varied HRTs (3 and 4 days). Results showed that although HSSF wetlands are effective in removing TN from the wastewater, the substrate type and retention times have a major effect on the removal efficiency (Shuib, N. and Baskaran, K., 2011).

ICWs have also proven to be effective in the removal of nitrogen from wastewater, resulting in high removal efficiencies of over 80% with an average $\text{NO}_3^- \text{N}$ removal of 96.9% over a 2 year study period found by Dzakpasu, M., et al., (2011). However, the previously mentioned study by Dong, Y., et al., (2013) found that although a high performance was achieved over the 2 year period, there were significant reductions found when hydraulic loading rate was increased, which is similar to the findings related to ammonium removal.

A study in Annestown, Ireland tested the long-term performance of ICWs in treating wastewater and found that the overall removal of nitrate-nitrogen over the 7 year study period was 86.8%, proving that the system remained effective over time. However this level decreased by 6.2% in 2007 which could suggest that efficiency will eventually decrease with wetland maturity, although this is not statistically significant (Mustafa, A., et al., 2009).

Overall it can be seen that both HSSF and ICW systems are effective in the removal of nitrogen, however, an increased HLR or wetland maturity, may reduce the overall performance of either of the wetlands.

2.9.3 Treating Phosphorus

Wetlands are known for their ability to retain phosphorus through a number of biological and physical processes (Harrington, R., et al., 2009). The emergent vegetation used within constructed wetlands provide an additional source of organic matter to the wastewater which retains the phosphorus until degradation occurs. However, due to prevailing anaerobic conditions within the wetland, degradation is inhibited and thus, maintaining these anaerobic conditions is critical to the subsequent phosphorus retention of the wetland. Therefore constructed wetlands should be designed accordingly with an appropriate water depth to allow vegetation growth as well as detritus accumulation (Harrington, R., et al., 2009).

ICWs were originally designed to treat wastewaters with a high concentration of phosphorus such as those found in agricultural activities. Thus, it is not surprising that these systems

perform quite highly in total phosphorus removal, however there are variations in research as to how well they perform under different conditions

Scholz, M. et al., (2007) highlighted that phosphorus removal in wetlands was the most effective in the first 3 years of operation and showed high variations in reduction between summer and winter months (Dunne, E. J., et al., 2005). A later study by Scholz, M. et al., (2010) found a 90% reduction of Molybdate Reactive Phosphorus (MRP) concentrations with no significant differences between summer and winter months. This study also found that phosphorus removal did not vary with wetland maturity, despite earlier suggestions that phosphorus removal becomes inefficient after 5 years.

Dzakpasu, M. et al., (2014) also evaluated the effects of long term Phosphorus loadings and hydrological inputs on Phosphorus treatment over a four year period at an ICW system at Glaslough (Figure 2.8). Average mass reductions of 91.4% were found although there was an overall reduction in mass retention with increased effluent flow volumes. This study also identified that young CWs (1-2 years) often have retention in excess of 90% but this rate declines sharply after 4 years, confirming Scholz's earlier statement.

Mustafa, A., et al., (2009) tested the long term performance of Annestown ICW system in Ireland and found the overall removal efficiency of MRP was 93.2% with no significant reduction with wetland maturity which is contradictory to Scholz, M., (2007) and Dzakpasu, M., et al., (2014). This study however, also found that removal efficiencies were highest in spring (95.7%), followed by autumn (94.9%), winter (93.2%) and then summer (90.7%) which is agreeing with Scholz, M., et al., (2010).

Dong, Y., et al., (2011) tested the impact of hydraulic loading and seasonal variations MRP within a constructed wetland and found that mass removal efficiency varied between 99.5% in spring and 62.5% in autumn which was likely to be due to variations in loading rate from low in spring to high in autumn, again confirming with Scholz, M., et al., (2010) and Mustafa, A., et al., (2009).

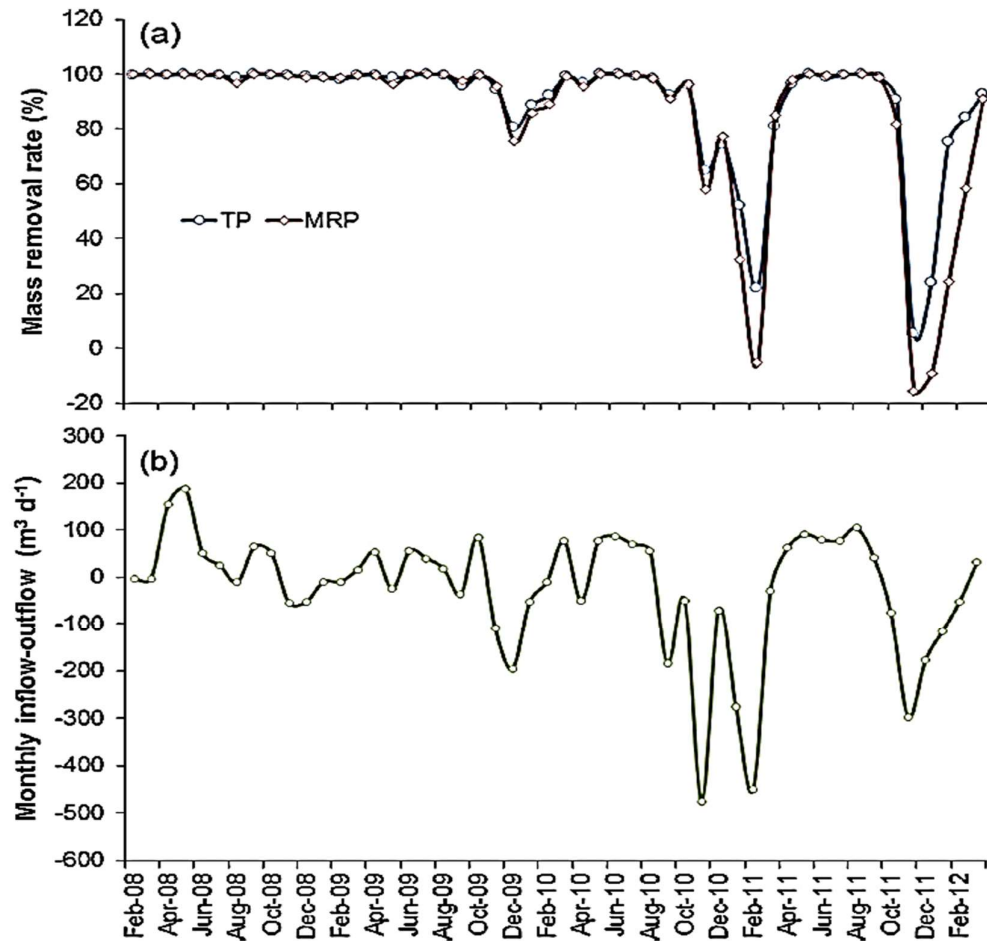


Figure 2.8 Phosphorus removal over a 4 year period at Glaslough ICW (Dzakpasu, M. et al., 2014).

Despite the inconsistency of results on ICW performance under various conditions, the overall removal rate over time remains high for phosphorus. HSSF wetlands have also proven that their ability to remove phosphorus is much more than other common wastewater contaminants. Both HSSF and ICWs can achieve high removal rates of Phosphorus and have been proven to be effective in doing so.

2.9.4 Treating Chemical Oxygen Demand (COD)

Due to the natural developments involved in the operation of a constructed wetland, the reduction of Chemical Oxygen Demand (COD) is particularly high in comparison to other wastewater treatment methods and both ICWs and HSSFs have proved successful.

COD removal of 78.7% was found within a constructed wetland treating eutrophic wastewater, even under high concentrations and shock loading rate (Shui, Y., et al., 2011). Dong, Y., et al., (2011) found a reduction in COD removal efficiency from 97.87% in spring to 84.24% in autumn. It was suggested by Dong, Y. et al., (2011) that this could be due to the immaturity of the wetland system leading to a lack of microorganisms which are crucial for the reduction of COD. This disputes a study by Mustafa, A., et al., (2009) who found an overall long-term removal efficiency of COD of 94.9% with no significant reduction over time throughout the 7 year study period.

The previously mentioned study by Shuib, N., and Baskaran, K., (2011) testing the performance of HSSF wetlands using three different substrates at varied HRTs also investigated the reduction of COD as well as other contaminants. Results showed that reducing the HRT to 3 days showed a slight decrease in the COD removal efficiency to 85 % using zeolite, however, the gravel and alum sludge substrates showed an increase in removal at 93% and 91% respectively. Again, this study would suggest that both the substrate type and HRT can have a significant effect on the removal efficiency of organic matter within HSSF systems, although removal efficiency still remained high (Shuib, N. and Baskaran, K., 2011).

Again, it can be concluded that both HSSFs and ICWs can be effective in the reduction of COD for various wastewaters. However, there are disputes as to whether or not seasonal variations or wetland maturity can impact on either, although removal rates even at a limited performance are still adequate.

2.9.5 Treating Biological Oxygen Demand (BOD)

As with COD, the natural existence of biological organisms within constructed wetlands means that they are particularly effective in the reduction of BOD from contaminated wastewater, especially in relation to ICWs.

A study on the long term performance of ICWs in Ireland found a BOD reduction of 97.6% which is similar to comparable FWS systems in the USA, but higher than other wetlands treating similar influents (Mustafa, A., et al., 2009). A similar study in Ireland found that a newer constructed wetland system at Glaslough had a BOD removal of 99.4% which was higher than the more mature system at Dunhill with 95.2%, contradicting previous theories that removal increases with maturity (Kayranli, B., et al., 2009).

Studies have also shown that BOD removal can be slightly impacted by seasonal variations from 99.37% in spring to 96.29% in autumn (Dong, Y., et al., 2013), although these variations do not cause significant reductions in the overall performance of the wetland.

Constructed wetlands have also shown potential to reduce BOD from highly toxic wastewater sources. For example, a lab study on the effectiveness of constructed wetlands for the tertiary treatment of petroleum refinery effluent found that average BOD₅ removal was as much as 80% and overall toxicity of the wastewater was also reduced (Huddleston, G. M, et al., 2000).

Overall, it can be concluded that constructed wetlands are effective in the removal of BOD from various wastewaters, especially ICWs which tend to perform higher than other types of wetlands.

2.9.6 Treating Total Suspended Solids (SS)

Total Suspended Solids (SS) removal is generally very efficient within constructed wetlands, however, increases in hydraulic loading rate and subsequent reductions in retention time have been known to reduce the performance as the high rate does not allow the sediment adequate time to settle within the ponds (Dong, Y., et al., 2012). A SS removal efficiency of 93.7% was recorded in a long term study of the 15 pond ICW in the Annesvalley Catchment Area, Ireland, which was explained by the large area and subsequently high retention times (Mustafa, A., et al., 2009).

A similar study in Ireland found that a newer constructed wetland system at Glaslough had a SS removal of 99.5% which was higher than the more mature system at Dunhill with 97.2%, contradicting previous theories that removal increases with maturity as shown in Figure 2.8 (Kayranli, B., et al., 2009). It should be noted however that Glaslough had 5 ponds within the ICW, while the system at Dunhill comprised of 4 Ponds, which may have contributed to the poorer performance of SS removal.

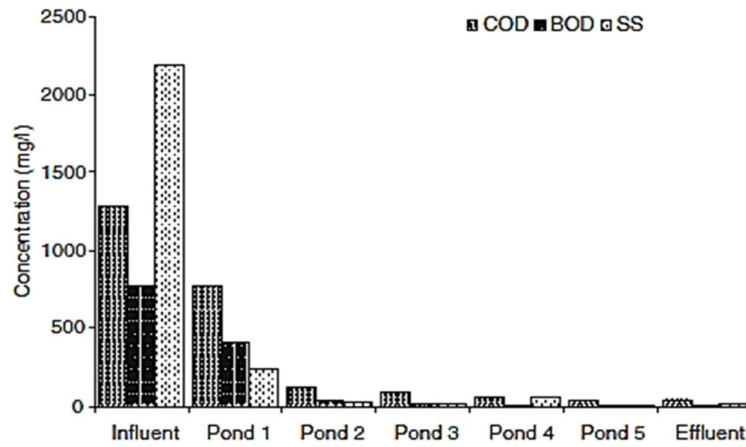


Fig. 5 Biochemical oxygen demand (*BOD*), chemical oxygen demand (*COD*), and suspended solids (*SS*) concentrations for the integrated constructed wetland system in Glaslough

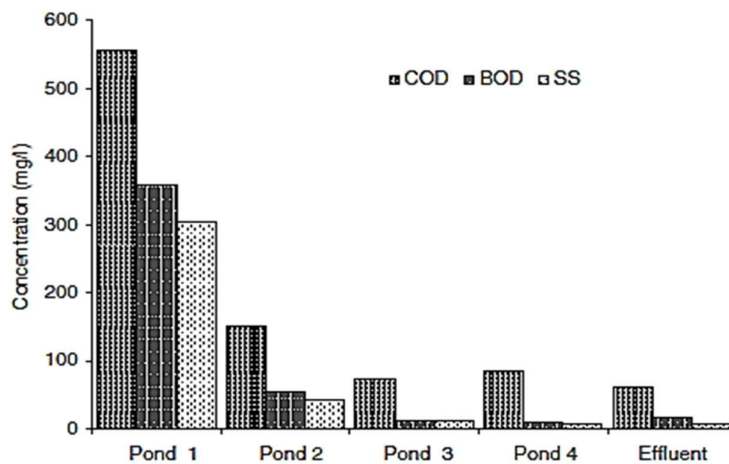


Fig. 8 Biochemical oxygen demand (*BOD*), chemical oxygen demand (*COD*), and suspended solids (*SS*) concentrations for the integrated constructed wetland system in Dunhill

Figure 2.9 Contaminant removal comparison between 1 year old system at Glaslough and 5 year old system at Dunhill (Kayranli, B., et al., 2009).

2.9.7 Microbial Removal

Another concern in wastewater management is the treatment of microbial organisms. These organisms allow for the growth of bacteria or faecal coliforms which can have a significant risk to human health. HSSF and ICW systems have proven to be capable of removing microbes from the wastewater, however, ICWs have demonstrated a particularly high performance rate.

Boutilier, L., et al., (2009) suggested that faecal coliform removal (particularly E-Coli) in treatment wetlands was due to several mechanisms, including adsorption, sedimentation and more significantly the inactivation of the coliform due to the absence of sediment (Boutilier, L., et al., 2009).

McCarthy, G., et al., (2011b) studied the microbial removal from liquid piggery wastewater in an ICW under 4 different treatment methods of standard, effluent recycling, high nutrient loading and high flow rate. Results showed that flow through the cells reduced mean counts of coliform, yeasts, moulds and spore-forming bacteria across all treatments despite seasonal variations. McCarthy, G., et al., (2011a) investigated the removal of pathogenic and indicator micro-organisms in ICW systems treating agricultural wastewater.

Results from this study were similar to McCarthy, G., et al., (2011b) in that constructed wetlands proved effective in the removal of *Escherichia coli* and *Enterococcus*, and any detected *Salmonella* within the influent, was no longer detected in the effluent. These studies show how ICWs are effective in removing most of the microbes within the wastewater, even under different loadings and seasonal variations, demonstrating the potential for constructed wetlands to be implemented as a means of treating high concentrations of organic waste.

2.9.8 Treating Other Contaminants

As well as the more common contaminants discussed above, constructed wetlands have been known to be successful in the reduction of heavy metals (Grisey, E., et al., (2012); Korsah, P. E., et al., (2014) Sultana, M., et al., (2015)), Phthalate Acid Esters (Zhou, Q.H., et al., (2005); Xiaoyan, T., et al., (2015), Hydrocarbons (Korsah, P. E., et al., 2014), Monochlorobenzene (MCB) (Braeckevelt, M., et al., 2007a; 2007b), antibiotics and Antibiotic Resistance Genes (ARG) (Chen, J., et al., (2014), Chen, J., et al., (2016), Choi, Y., et al.,(2016)) and estrogenic

hormones, progesterone and testosterone (Vymazal, J., et al., (2015); Papaevangelou, V.A., et al., (2016)) from wastewater from various sources.

2.10 Variables that Influence the Treatment Performance of Constructed Wetlands

The performance of a constructed wetland in treating wastewater is influenced by a number of variables. These include design, hydraulics, climate and planting.

2.10.1 Water Depth

Water depth influences the hydraulics of the wastewater flow through the system which can either enhance or limit treatment performance. A greater water depth will increase the volume of flow through the wetland and, providing the surface area does not change, should reduce the hydraulic loading rate (HLR), subsequently increasing HRT. The higher HRT is associated with higher performance rates and thus, it could be assumed that a higher water depth would enhance overall wetland performance. However, Cui, L., et al., (2012) found that a greater water depth had a negative impact on plant growth. Performance of the wetland was negatively correlated with depth. This conflict in opinion suggests it is important to design the constructed wetland with an appropriate water depth which will allow for an adequate HRT without impacting on vegetation performance.

2.10.2 Material Used in Pond Construction

The depth and composition of material used to make the pond bed influences performance. HSSF wetlands tend to use a mix of gravel, sand and soil, while ICWs use just soil. Soil allows for the processes involved in wastewater treatment, while sand and gravel allow for more efficient flow through the system. Soil absorbs contaminants from the effluent and retains it within its structure. A study of plants and sediments used in the treatment of wastewater in ICWs found that 74% of phosphorus and 52% of nitrogen was removed and stored within the soils and sediments. This is substantially higher than the <1% of each stored within the plants (Mustafa, A., Scholz, M., 2011b). This illustrates the role of soil and sediment in retaining the nutrients is more influential to wetland performance than the role of plants (Figure 2.10).

Table 4 Nutrient storage estimates in vegetation and soil/sediments in the studied integrated constructed wetlands

Nutrient component	Summer (kg)	Winter (kg)	Difference: summer–winter (kg)
Total nitrogen			
Plant	50.9	35.2	15.7
Soil and sediment	6,057	4,201	1,856
Total	6,107.9	4,236.2	1,871.7
Total phosphorus			
Plant	13.7	7.6	6.1
Soil and sediment	899	662	237
Total	912.7	669.6	243.1

Figure 2.10 Nutrient storage comparison between sediment and plants (Mustafa, A., Scholz, M., 2011b).

The removal of contaminants involves processes which may be directly, or indirectly influenced by soil type (Wu, S., et al., 2014). The removal of nitrogen from wastewater requires the process of denitrification. This needs organic carbon to allow for the exchange of electrons. Much of the organic carbon present in constructed wetlands is sourced from the wastewater and the soil itself (Wu, S., et al., 2014).

The soils physical structure is also important. Garcia, J., et al., (2004) illustrated that a finer media allowed for a more effective hydraulic movement within HSSF systems by reducing dispersion. Wu, S., et al.,(2014) explains that soil structure allows for various microbial biofilms to develop which are vital for the treatment of BOD and COD as a more porous matter allows for a greater biofilm to be achieved. Morato, J., et al., (2014) confirms both these findings, demonstrating that a finer granulometry had a significant positive impact on the biofilms of HSSF systems, allowing for more effective treatment of Total Coliforms, Clostridium spores, and E. coli.

Mustafa, A., et al., (2009) stated that most of the biological degradation of wastewater occurs within these biofilms present on the sediment and soils of the wetland suggesting porosity and granulometry are key contributors to the overall performance of constructed wetlands. However, Hijosa-Valsero, M., et al., (2010) found that the presence of soil was not necessarily crucial for the development of microorganisms as the plants themselves provide an adequate surface for the establishment of biofilms.

The characteristics of the soil, in terms of particle size, organic content and iron and aluminium concentrations, have also proven to have a significant influence on the wetlands ability to retain phosphorus with those with higher clay content and iron and/or aluminium concentrations being more effective (Mustafa, A., et al., 2009). A poor-quality soil structure may therefore lead to limited treatment of wastewater due to reduced absorption and may even allow for leaching into the subsurface as discussed by Dzakpasu, M., et al., (2012).

Soil can indirectly influence hydraulic flow, plant growth and development rate (Stottmeister, U., et al., (2003); Garcia, J., et al., (2004)). A layer of topsoil of around 200-300mm is considered ideal for the growth and development of most macrophytes in a surface flow wetland like ICWs (Scholz, M. and Lee, B., 2005). Therefore, the composition, quality and depth of soil must be considered within the design of a constructed wetland to ensure that optimum performance can be achieved through adequate soil absorption and plant development.

2.10.3 Pond Geometry and Landscape Fit

Pond geometry is the overall layout and structure of the constructed wetland in terms of shape, size and number of ponds. HSSF systems tend to be a series of rectangular ponds constructed in linear sequence compared to the curved, non-linear geometry of the ICW. This difference can be explained by the hydraulic related performance of each system.

HSSF systems have a higher soil content than ICWs. The flow rate through the system is restricted allowing for a longer treatment process. The rectangular design is suited to the subsurface flow wetlands as it allows for effective hydraulic movement and higher treatment efficiency (Garcia, J., et al., 2004). However, if the length: width ratio is too high flow through the system will be increased, despite the soil restriction, having a negative impact on performance. Gorra, R., et al., (2014) found that an irregular shaped HSSF can be effective in the removal of BOD from high organic loadings suggesting that this design aspect should be considered for future HSSF installations.

ICW systems have a higher water content than HSSF. By integrating curves and dividing the area into a number of ponds, the flow rate is reduced and HRT increases (Scholz, M., et al., (2007a; 2007b)). If ICWs were to implement the same geometry as HSSF wetlands, or have a higher length to width ratio, the flow rate would be too high for the wastewater to be appropriately treated and the system would be ineffective (Scholz, M., et al., 2010).

Wetland geometry can impact performance through the area and number of wetland ponds. This is especially true for ICWs where performance is not only based on wastewater treatment, but also on the wetlands ability to integrate into the surrounding area. As such, ICWs must cover an adequate surface area, which is divided into a number of curved ponds to allow for appropriate HRT, whilst still maintaining the appearance of a natural system. Dunne E. J., et al., (2005) tested the use of 3 ponds to treat farmyard wastewater covering an area of twice the farm yard.

Treatment performance was as much as 80-90% in summer months. This reduced in winter to around 50% and required a fourth monitoring pond to aid in the reduction of BOD₅ and sedimentation before being released into the nearby river. Scholz, M., et al., (2007a; 2007b) suggested that 4 ponds or more covering an area of 1.3 times the contributing area would be a more effective option and that the curvier the ponds are the better as this helped with HRT and made the system more effective (Figure 2.11).

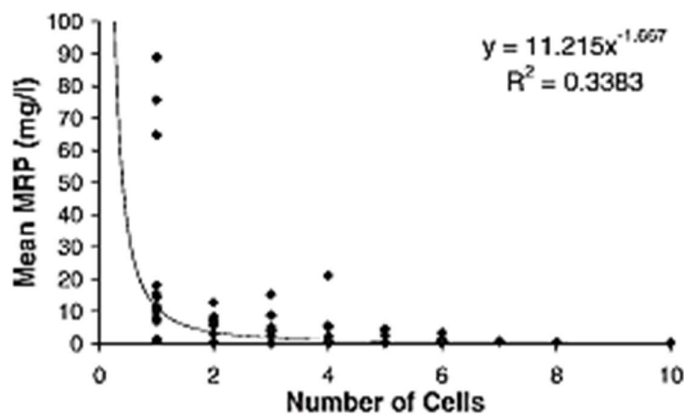


Figure 2.11 Reduction of MRP with increased number of cells (ponds) (Scholz, M., et al., 2007a; 2007b).

Kayranli, B., et al., (2009) also suggested that the curvier design of an ICW at Glaslough could be a potential reason for better efficiency over the more systematic ICW at Dunhill, rather than the difference in cell numbers. Becerra-Jurado, G., et al., (2012) however recommended that a surface area of more than 1.3 times farmyard area and the number of ponds should increase from a minimum of 4 to at least 5 as this would be better for the removal of MRP as well as biodiversity enhancement. It was suggested that having the ponds close together with shore sloping and a mosaic layout will allow for a better biodiversity community connectivity,

whilst still keeping with the low aspect ratio of <2.2 required for adequate pollutant removal (Becerra Jurado, G., et al., 2009).

This suggest that wetland geometry and landscape fit is not only important for the performance of the constructed wetlands in treating wastewater, but also their ability to integrate into the landscape and create a naturalised system capable of enhancing local biodiversity.

2.10.4 Hydraulic Interactions

2.10.4.1 Hydraulic Loading Rate

According to Kadlec and Wallace (2008), Hydraulic Loading Rate can be defined as the ‘rainfall equivalent of whatever flow is under consideration’ and is calculated using the following equation:

$$q = Q/A$$

Where q = HLR (m/d); A = wetland area (m²); Q = water flow rate (m³/d)

This definition is commonly used at the inlet of the wetland to calculate the HLR of influent of FWS wetlands. The HLR of constructed wetlands has been investigated for some time to determine its effects on, and contribution to, the wetlands performance. Most of these studies have concluded that HLR has had somewhat of an impact on the efficiency and/or effectiveness of the wetlands ability to treat various contaminated wastewaters. Garcia, J., et al., (2005) found HLR and water depth were more significant contributors to performance of the wetland than either aspect ratio or granular size. Harrington, R. and McInnes, R., (2009) concluded that HLR is crucial for the efficiency of treatment and that the design of constructed wetlands should be based on developing the most efficient HLR and subsequent performance.

2.10.4.2 Factors that Influence HLR

As HLR is determined using water flow rate and wetland area, it is relatively sensitive to variations in environmental factors such as climate and vegetation cover, as well as physical

factors of surface area and pond depth. Pei, Y., et al., (2010) investigated the influence of seasons on HLR and HRT within a Riparian wetland (adjacent to a stream or river), and the subsequent impact this had on the performance of nitrate removal. The study found that HLR was significantly impacted by temperature and climate, which then influenced the wetlands ability to remove nitrates from the water.

Beebe, D., A, et al., (2014) and Tuttolomondo, T., et al., (2016) illustrate how water flows through wetland systems are greatly affected by various evapotranspiration rates, subsequently impacting on HLR, HRT and the overall performance of the system.

As vegetation loses more moisture in hotter temperatures due to evapotranspiration, it must then uptake more moisture from the wetland in order to survive, consequently reducing the water levels of the wetland. Thus, not only does climate impact on the water levels directly through evaporation and precipitation, but it can also have indirect influences due to its effects on vegetation growth and performance, illustrating how plant cover can correspondingly influence HLR.

Physical characteristics of the wetland can impact HLR. Seeger, E., M., (2013) found hydraulic flow was dependent on pond depth, the planting of plants and the position of the outlet. Water depth can influence HLR as altering the depth of the pond changes the volume of water within the pond. This then alters the flow rate (Q) providing the area of the pond (A) remains constant, which consequently impacts on the performance of the constructed wetland (Alley, B. L., et al., 2013).

2.10.4.3 Impact of HLR on Constructed Wetland Performance

Ingersoll, T. L., et al., (1998) studied the effects of HLR and carbon addition to nitrate removal and found that higher HLR meant decreased nitrate removal; however, a higher carbon addition meant higher nitrate removal. This would suggest that a lower flow and higher pollutant concentration would be a more efficient method of treating wastewater. This is confirmed by Dzakpasu, M., et al., (2014) who varied the input loading rates of Phosphorus to test the effect this would have on treatment performance. Li, X., et al., (2007) found that removal efficiency could be improved if HLR was increased but with a lower pollution

concentration, which is contradictory to both Dzakpasu's and Ingersoll's findings (Dzakpasu, M., et al., (2014); Ingersoll, T. L., et al., (1998)).

In terms of pollutant concentration loading, Harrington, C. and Scholz, M., (2010) examined the effect of nutrient loading, hydraulic loading and effluent recycling on the treatment performance of anaerobically digested piggery wastewater. They tested the removal of total organic nitrogen, ammonia-nitrogen, nitrate-nitrogen, and MRP and found that both low and high hydraulic loading proved effective, which is also contradictory to Dzakpasu's study, although higher rates did prove challenging for the removal of ammonia-nitrogen.

Dong, Y., et al., (2011) found similar results to Harrington, C. and Scholz, M., (2010) with marginal differences in performance related to high and low HLR; however, it was indicated that this was possibly due to other external factors and it was concluded overall that at high HLR the effectiveness of the ICW is low due to a reduced retention time. This was then confirmed through later studies by Harrington, C., et al., (2012) on the performance of nutrient removal of separated swine wastewater (Table 2.6).

Table 2.6 Effect of different nutrient loads and retention times on contaminant removal
(Harrington, C., et al., (2012) Table 2).

	Normal in	Normal out	% reduction	Recycle in	Recycle out	% Reduction	HNL ^a in	HNL ^a out	% Reduction	HFR ^b in	HFR ^b out	% Reduction
Ammonia	99.46	0.53	99.5	99.46	0.18	99.9	185.72	0.69	99.7	99.46	1.94	98.1
MRP	1.62	0.03	98.1	1.62	0.04	97.5	3.2	0.05	98.5	1.62	0.05	96.9
Nitrite	1.85	0.08	95.7	1.85	0.06	96.8	8.58	0.16	98.2	1.85	0.45	76.7
Nitrate	6.96	2.33	66.6	6.96	1.44	79.1	2.95	4.78	0	6.96	8.42	0
TON	9.45	2.41	74.5	9.45	1.51	84.1	12.19	4.94	60	9.45	8.87	0

^a High nutrient loading

^b High flow rate

However, other studies have found that an increased HLR was effective for treating TSS and COD but not for N and P (Guo, Y., et al., (2014); Calheiros, C. S. C., et al., (2009)) suggesting that the effects of HLR could be specific to the type of contaminant being treated. Çakir, R., et al., (2015) tested the effects of HLR specifically on HSSF systems treating domestic wastewater from local communities and concluded that a reduced loading rate was statistically relatable to

higher treatment performance and suggested that these relationships be used for scaling purposes for future HSSF design.

Studies have also implied that altering HLR by either flow rate or concentration could have impacts on the various organisms living within the wetland such as plants and organisms (Huddleston, G. M., et al., (2000); McCarthy, G., et al., (2011b)). McCarthy indicated that higher nutrient loading had different effects than higher flow rate on different micro-organisms. Allen, C. R., et al., (2013) also found that different species of plants performed differently to the treatment of nitrogen when HLR and HRT was varied within a batch-loaded SSF wetland system. These findings from McCarthy and Allen would suggest that hydraulic loading can have various impacts on the treatment of wastewater depending on the characteristics of each particular site.

2.10.4.4 Hydraulic Retention Time

Hydraulic Retention Time (HRT) describes the length of time it takes for influent to pass through the wetland and discharge as effluent. Kadlec, R. and Wallace, S., (2008) define HRT as 'the wetland water volume involved in flow divided by the volumetric water flow' as seen in the following equation:

$$t = V_{active} / Q$$

Where t = detention time (d); V_{active} = volume of wetland containing active flow (m^3); Q = flow rate (m^3/d)

Like HLR, HRT has been the focus of many studies relating to optimising the efficiency of constructed wetlands, yet unlike HLR, there seems to be a general consensus as to how HRT impacts on wetland performance with higher HRTs leading to overall better treatments. However, there appears to be a slight difference in opinion as to the importance of HRT in influencing such performance compared to other factors such as HLR. For example, as already noted, the study by Garcia, J., et al., (2005) found that the aspect ratio and granular medium size of a constructed wetland, which impact on HRT, contributed to the treatment performance, but were not as significant when compared to HLR and water depth. Harrington, R. and McInnes, R., (2009) also established that HLR is crucial for the efficiency of treatment of

an ICW, but that this was to allow for an adequate HRT in order to give the wetland the opportunity to undergo the appropriate treatment processes.

2.10.4.5 Factors that Influence HRT

HRT is sensitive to variations of a number of physical and environmental factors, including HLR itself. Thus, it could be agreed that factors that influence the HLR, will also have an indirect influence on HRT. In terms of physical factors for example, one feature which would have an indirect influence on HRT through HLR would be the surface area of the pond. In theory, a lower HLR means a higher HRT, however, if the footprint of the constructed wetland is high then HRT will be subsequently high meaning the impact of varying HLR on HRT would be marginal (Dong, Y., et al., 2011). If, however the surface area of the pond is small, altering HLR will have significant impacts on the HRT and have major influences on the performance of the wetland. Another factor that would influence HRT indirectly through altering HLR would be the depth of the wetland ponds. As previously mentioned, altering the depth of the pond, and subsequently the ponds volume (V), has an impact of the rate of flow (Q) and overall HRT which can have significant implications for the treatment performance of the wetland (Alley, B. L., et al., 2013).

In terms of environmental factors, HRT is also affected by variations in climate, vegetation cover and soil composition like HLR. Pei, Y., et al., (2010) illustrated how different seasons had an impact on the wetlands ability to uptake moisture and nutrients from the wastewater. As a result, the HLR, and corresponding HRT, were influenced significantly having a subsequent impact on the overall performance on the wetlands ability to remove nitrates.

Paudel, R., et al., (2013) on a large CW in the USA looked at modelling how variations of plant density could impact on HRT. The results identified that higher vegetation density would result in lower HRT, which is agreeing with findings by Tuttolomondo, T., et al., (2015). However, Paudel, R., et al., (2013) illustrated how too high a vegetation density could result in a higher HRT which could lead to excessive water levels within the wetland becoming detrimental to plant performance and thus treatment efficiency.

Another way in which HRT could be altered would be through the process of effluent recycling which involves taking the effluent from the outlet and allowing it to flow back into the inlet of the pond to be retreated. Effluent recycling has been found to substantially increase HRT

subsequently improving performance of wastewater treatment, especially with regards to Ammonia-Nitrate, MRP and Nitrates (Harrington, C., et al., 2012).

2.10.4.6 Impact of HRT on Constructed Wetland Performance

As with HLR, the sensitivity of HRT to external factors gives rise to a number of implications on the performance of constructed wetlands and the treatment of contaminated wastewater. Although it has been previously highlighted in chapter 2.10.4.5 that there is a general understanding within research that higher HRT leads to a better treatment efficiency of the wetland, there are studies that would suggest that there is a level at which this higher HRT peaks and then begins to become inefficient.

For example, a study by Zhao, Z. et al., (2011) on HSSF wetlands found that HRT had significant effects on the removal of COD, TP and Nitrate nitrogen but not on ammonia and nitrite, showing how different HRT can impact on various contaminants within the same wetland. Other studies on FWS wetlands have found that a higher HRT also had a positive correlation with Phosphorus removal (Lu, S. Y., 2009) and TN (Garcia-Lledo, A., et al., 2011) showing similar positive results for different contaminants within the same type of wetland.

A more recent study by Mirunalini, V., et al., (2014) found that higher retention times showed better treatment performance of BOD, COD, TSS, TDS, TN and TP for both dairy wastewater and domestic wastewater illustrating a positive correlation despite the contaminant and wastewater type (Table 2.7). Mirunalini also suggested that performance may peak at an even longer retention time; however, it was also reported by Headley, T. R., et al., (2005) and Ayaz, S. C., (2008) that a longer HRT may cause the inefficient removal of BOD.

Table 2.7 Percentage removal efficiency of dairy and domestic wastewater against retention time (Mirunalini, V., et al., 2014).

Parameters	Removal of dairy wastewater (%)			Removal of domestic wastewater (%)		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
BOD	20.0	30.6	25.3	65.7	79.4	92.6
COD	56.0	62.1	66.0	50.7	69.7	86.8
TSS	73.4	76.9	79.3	58.3	91.8	96.8
TDS	69.2	69.7	72.3	60.9	70.8	84.3
Nitrogen	29.8	35.0	37.3	13.9	25.5	44.1
Phosphorus	14.5	35.4	42.5	37.5	62.5	75.0

Although the general outcome appears to vary slightly according to wetland type and the concentration/type of contaminants being treated, it can be concluded that there is a positive correlation between HRT and wetland performance, although there are exceptions to the rule. It would be fair to state that these exceptions would depend upon a number of peripheral issues such as the size and/or type of wetland under investigation, its climate, the external factors which contribute to its performance and the type and volume of wastewater that is being treated.

2.10.5 Climatic Conditions

There have been a number of studies conducted which relate the performance of constructed wetlands to seasonal and climatic variations. Performances of phosphorus, MRP, COD and BOD and trace elements have all been found to be reduced in autumn and winter compared to spring and summer in both ICWs and HSSF systems (Dzakpasu, M., et al., (2011; 2014); Dong, Y., et al., (2011); Burgoon, P., S., et al., (1999); Rai, U. N., et al., (2015)).

The climate of the local area can have an impact on the performance of constructed wetlands in a number of ways. Factors such as temperature, wind and precipitation can all influence the hydraulics and performance of plants within the system, having indirect impacts on the overall performance. Precipitation and wind can have a major impact on the hydraulic processes within the wetland as factors such as flooding, drought and evaporation can influence the HLR and HRT of the wetland.

One study found that the discharge levels from an ICW was greatly reduced throughout summer months due to the increase in evaporation rates caused by associated higher temperatures (Forbes, E. G. A., et al., 2011). Temperature can also influence the hydraulics of the wetland by altering the rate of evaporation or transpiration by plants, having a subsequent impact on the transport of water through the hydrosol where many biological and chemical treatment processes occur (Beebe, D. A., et al., 2014). Low removal efficiencies for BOD, COD and nitrogen in autumn and winter is said to be due to reduced microbial activities and lower nitrification/ denitrification rates caused by lower temperatures, while lower MRP and phosphorus removal could be due to the reduced plant uptake in colder temperatures (Dong, Y., et al., 2011).

However, others have demonstrated that wetlands performed better at removing BOD in winter months and nitrates in summer months, suggesting that treatment performance may be subject to the contaminant involved (Gorra, R., et al., 2014). Temperature is also known to have an impact on the growth of different plant species within the wetland, and their ability to transfer oxygen required for treatment processes, again having an indirect impact on the overall performance (Stein, O. R. and Hook, P. B., 2005).

Although a higher precipitation rate can be associated with lower performance due to increased flow and reduced retention times, one study on the treatment of wastewater containing heavy metals found that treatment performance was higher in spring when rainfall was higher. It was suggested that the increased precipitation may have caused a dilution effect and lixiviation (Grisey, E., et al., 2012). Another study found that seasonal variations in wetlands was dependent upon the plant species as some species perform better in summer and others in winter (Yang, Q., et al., 2007). However, it has been demonstrated that although planted systems perform better during warmer summer months, unplanted systems perform better throughout the winter months (Karathanasis, A. D., et al., 2003). This evidence would suggest that climate can influence wetlands in different ways, depending on the type of plants or contaminants involved, resulting in positive or negative impacts.

2.10.6 Role and Type of Plants

Plants are a major contributor to the performance of constructed wetlands due to their ability to influence hydraulic flow, provide habitat for microorganisms, absorb nutrients, and filter through sedimentation. This section illustrates the important role plants play in the treatment

process, and how the type of species can determine the effectiveness and efficiency of treatment of various contaminants.

2.10.6.1 Role of Plants

Brix, H., (1997) details how macrophytes play an important role in constructed treatment wetlands by contributing to the physical, chemical and biological processes involved in wastewater treatment, as well as providing an aesthetically pleasing addition to the landscape. Despite this evidence, further studies have continued to investigate the performance of planted and unplanted wetlands in treating a variety of wastewaters in order to establish if the presence of plants is crucial. Results have found that although both planted and unplanted systems were effective, planted systems were more effective in the removal of total phosphorus and total nitrogen, but not for organic removal (Yang, Q., et al., (2007); Elsaesser, D., et al., (2011)). Conversely, other studies have shown significant differences between planted and unplanted systems with planted obtaining a higher average removal rate than unplanted systems (Sultana, M., et al., (2015); Ranieri, E., et al., (2015) Türker, O.C., et al., (2016)).

The short study period for the previous studies should be noted however as an earlier study found that plants were not as effective in storing nutrients as the wetland matures. Results of one particular study found that less than 1% of nitrogen and phosphorus had accumulated within the plants over a 7 year period compared to the 74% of phosphorus and 52% of nitrogen stored within the wetland soils (Mustafa, A., and Scholz, M., 2011). This study would suggest that the wetlands' soils could be a more important factor in the long-term removal of contaminants from wastewater.

Plants can also have an impact on the performance of constructed wetlands as their presence allows other organisms to develop and thrive which are crucial to the treatment of wastewater. Fester, et al., (2014) demonstrates the importance of plants and their interactions within the ecosystem, providing wastewater treatment through phytoremediation. The report illustrates how plants are not only effective in contaminant removal themselves, but that they also support numerous communities of micro-organisms which are vital for the treatment of organic contaminants.

2.10.6.2 Types of Plants

Not only does the presence of vegetation play an important role in the performance of constructed wetlands, but the species type is also influential. Some species are more suited to particular types of wetlands, climatic conditions and wastewater contamination than others, and therefore, tend to perform better. Thus, it is important that the correct species is selected for the specific wetland being implemented.

For example, studies have found that some species are more effective in the removal of nitrogen and phosphorus than others (Dong, X. and Reddy, G. B., 2010) which could be due to particular qualities such as having a fine root biomass (Yang, Q., et al., 2007), or having a greater the abundance of microbes, or rhizosphere enzyme activity, relevant to the nutrient removal processes within a constructed wetland (Ge, Y., et al., 2011). Contrary to this, Meng, P., et al., (2014) and Rai, U. N., et al., (2015) found that there was no real difference in phosphorus removal overall across a number of different plant species but that the performance of each species varied greatly species across the different seasons. These findings could be a result of differences in seasonal performance rates of plant species as described by Allen, W., C, et al., (2002).

As there are differences in removal efficiency between species, it is important to select the appropriate species specific to the particular wetland from the design stage in order to optimise overall performance (Brisson, J. and Chazarenc, F., 2009). It is therefore recommended that plants should be selected on their BOD removal efficiency, growth rate, biomass production and the number of rhizobacterium present (Phewnil, O., et al., 2014), as well as their rate of evapotranspiration (Tuttolomondo, T., et al., 2015), their sensitivity to climatic conditions, and their ability to treat various contaminants (Taylor, C., R, 2009).

2.10.7 Summary of Key Variables that Impact Treatment Performance

Wetland design in terms of water depth, soil depth, soil composition, surface area, wetland shape, number of ponds and plant presence and species, all have an influence on the performance of both HSSF and ICW systems in treating wastewater, as well as the climatic conditions of the wetland location. These factors have shown to have an influential role in determining the hydraulics of the wetland flow, as well as impacting on the growth and

development of the various plant species. However, it can also be seen that each of these design principles have varying impacts on numerous types of wetland and wastewater. Thus, it is important that the appropriate design is selected for use in a specific wetland depending on the local climatic conditions and the type of wastewater being treated, to ensure that optimum results can be achieved.

2.11 Key Factors that Determine Constructed Wetland Performance

Despite constructed wetlands demonstrating a strong ability to effectively treat various types of wastewater, there are other issues which need to be considered in order to determine the overall performance of constructed wetlands. Factors such as land use, odour creation, social impacts, carbon footprint, economic performance, whole life costing, operation and maintenance and climate change mitigation, all contribute to the overall performance and value of constructed wetlands in various ways.

2.11.1 Impacts of Land Usage

As previously discussed in section 2.1, each wetland serves a different function and is capable of treating some contaminants and loadings better than others. As such, it is imperative that the design of the wetland used is effective and appropriate for these specific conditions. Thus, the surface area of the wetland is also specific to the type or level of treatment required and/or the physical and environmental conditions of the local area. As such, it is important to consider the amount of land available and its associated costs in order to determine which design of wetland would be most efficient, effective and sustainable.

Lucas, R., et al., (2014) identified land use and land availability as main challenges in the implementation of constructed wetlands in the UK (Lucas, R., et al., 2014, cited in Chang, C., et al., 2015). It is not surprising therefore, that according to Kadlec, R., H, et al., (2009) the sizing of constructed wetlands is the most reported design feature between wetland types. Due to the differences in designs and objectives of various wetlands, the surface area of ICWs is much greater than HSSF systems.

It could be assumed therefore, that HSSF wetlands have an advantage of a smaller land requirement than ICW systems, and subsequently reduced capital costs, which would be a major contributor as to why HSSF systems tend to be more widely used. However, the high performance rate of ICWs in treating highly contaminated wastewater means that these systems may still remain the more appropriate option to implement, depending on the quality of water being treated and level of output expected. Thus, the reduced cost of using a smaller HSSF wetland in terms of economic land value, may bring unexpected costs of reduced effectiveness. Also, the economic savings of land value from HSSF may not outweigh the social and environmental gain that can be obtained from using the larger area of the ICW system in terms of biodiversity enrichment and leisure facilities. Thus, it is essential that the decision makers are fully aware of the true costs of land usage by constructed wetlands before embarking upon the design, construction and operational phases.

Some innovations in the use of constructed wetlands for wastewater treatment have tried to reduce the amount of land required through the inclusion of artificial aeration or tidal flow operation which increase the oxygen capacity of the wetland and allow more effective treatment over a smaller area of land (Wu, S., et al., 2014). However, these methods come with a higher operation and maintenance cost compared to traditional constructed wetlands as shown in Figure 2.12 (Wu, S., et al., 2014).

There are costs and benefits associated with the use of land to implement constructed wetlands; however, there have been various advances made to try and integrate such systems into the local area in the hope of reducing the adverse impacts associated with the land take of both HSSF and ICW systems.

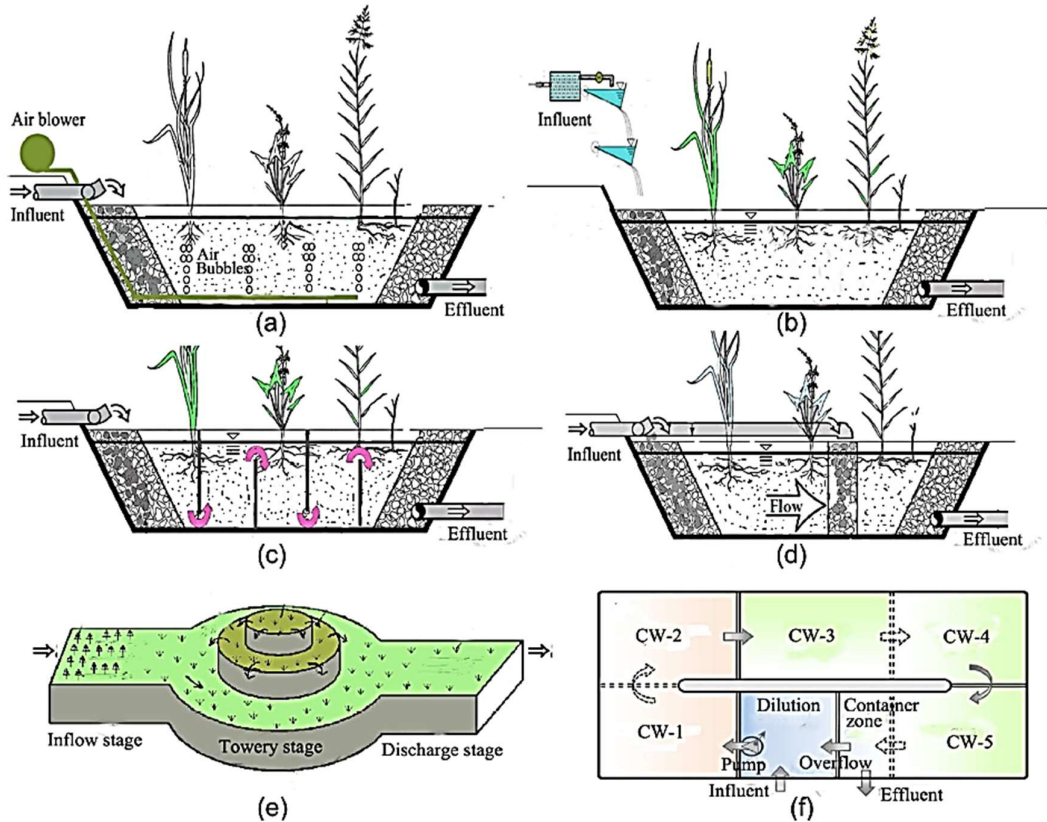


Fig. 1 - Intensified constructed wetlands (a, artificial aerated CW modified with graphical components from Wallace and Knight (2006); b, drop aerated CW modified with graphical components from Wallace and Knight (2006) and from Zou et al., 2012; c, baffled flow CW modified with graphical components from Wallace and Knight (2006); d, step feeding CW modified with graphical components from Wallace and Knight (2006); e, hybrid towery CW modified from Ye and Li, 2009; f, circular flow corridor CW modified from Peng et al., 2012).

Figure 2.12 Intensified constructed wetlands (Wu, S., et al., (2014)).

Some methods of this involve integrating the wetland systems into urban areas to make use of disused space or brownfield sites, bringing a more sustainable approach to urban development (Junge-Berberovic, R. and Graber, A., 2004). The report by Junge-Berberovic and Graber (2004) also identifies how the use of constructed wetlands within urban areas can help enhance the local ecosystem and increase the biodiversity within the area whilst providing a sustainable alternative to wastewater treatment.

Constructed wetlands have also been successfully implemented into urban residential areas where land availability is generally limited. For the wetlands to be fully integrated into such areas, they must be accepted by the local residents as part of their community. One particularly good example of this would be a small-scale study in China which investigated the

design of a fan-shaped HSSF wetland planted with ornamental aquatic plants which involved a land usage of just 0.5m²/pe, which coupled with the environmentally sensitive design gives rise to a very sustainable and viable approach (Zhao, X. et al., 2014).

As well as being able to integrate constructed wetlands into the local surroundings, there have been cases where the implementation of the wetland has enhanced and enriched the neighbouring area, improving not only the aesthetic landscape, but also providing an area for local wildlife to flourish. One example of this is reported by Kalin, M. (2011) who looked at the use of constructed wetlands to aid in the restoration of post-mining landscapes.

Another example as to how constructed wetlands could be used effectively to enhance the local area would be the Vallevecchia Wetland System in Northern Italy where 900ha of reclaimed wetlands were used to treat non-point pollution from agricultural activities. The wastewater is recycled through the system where it is then used for irrigation purposes during droughts or dry spells, as well as reducing the high nutrient load discharging into the Adriatic Sea which already has a problem with eutrophication (Carrer, G., M. et al., 2011). Again, this illustrates how wetlands can be reclaimed and rejuvenated to be used for treatment processes, providing a solution to on-going wastewater problems, whilst also contributing to the local environment and wildlife.

Semeraro, T., et al., (2015) demonstrated that constructed wetlands were capable of much more than the treatment of wastewater, providing the additional benefits of sustaining and enhancing wildlife biodiversity, on a global scale, as well as creating a potential area for educational and leisure opportunities. Thus, although it may seem that the large land requirement is a highly limiting factor in the implementation of constructed wetlands, ICWs are based on the design principles of integrating the wetland system holistically into the local landscape, using available geology, topography and ecology to construct an area which has purpose, robustness and sustainability.

Consequently, the reduction of land requirement is not of particular concern, with some studies finding additional benefits to increasing land take rather than limiting it. Beccerra-Jurado, G. et al., (2011) found that increasing the land usage from the ICW to 5 ponds or more would encourage wildlife into the area and improve biodiversity whilst also potentially being used as a leisure site for recreational or educational activities.

Overall, it can be seen that there are advantages and disadvantages to land use by constructed wetlands. HSSF systems require a smaller land take than ICWs but are typically less fitting with

the local landscape; however, new design approaches have improved their appearance and allowed for a more aesthetic implementation to urban areas. The larger land requirement of ICWs gives rise to a higher capital cost in the construction and development of the system, then again, the associated benefits of being wholly integrated into the local environment whilst providing an amenity suitable for educational and leisure activities may be deemed to be more valuable.

Also, although the land requirement for ICWs is high, the construction of this type of system can still be as much as half the price of a traditional WwTW and is capable of treating as much as 3 times more wastewater (Doody, D. et al., 2009). Thus, despite differences between wetland systems, there is reason enough to implement even the costliest of constructed wetland designs, as it is still much more sustainable than current industry practices.

2.11.2 Effects of Odour

It would be fair to assume that the use of constructed wetlands for wastewater treatment would give rise to an increase in odour in the surrounding area. However, very little research has been conducted to test odour levels associated with constructed wetlands, with only a few studies being concerned with the reduction of substances which have the potential to create odour (Ju, X., et al., (2014); Kadlec, R., H., et al., (1997); Lv, X. and Ruan, X., (2011)). It would therefore appear from the literature that odour development is not deemed to be of major concern in the enhancement of constructed wetlands. It is noted that the literature reviewed does not make reference to the impacts of odour caused by ICWs treating domestic sewage so ICWs cannot be disregarded as having no issues with odour and further studies would be recommended.

2.11.3 Social Considerations

Constructed wetlands are known for being environmentally-sensitive alternatives to traditional wastewater treatment works. However, in order for them to be truly sustainable, they must also be socially and economically viable.

ICWs are based on the principle that they must be environmentally, socially and economically acceptable, so issues of social impact are considered to be critical to the overall performance

(Harrington, R. and McInnes, R., 2009). The ICW at Glaslough for example was implemented with equestrian and walking trails to allow for more tourist based activities, which also complimented the tourist attractions of the local Castle Leslie Estate (Doody, D., et al., 2009). As a result, ICWs are normally well received by the local society as their environmentally sensitive design allows them to enhance biodiversity whilst permitting recreational and educational activities (Becerra-Jurado, G., et al., 2011).

This would be especially beneficial for urban areas, where the availability of green space for leisure is greatly limited. Constructed wetlands add valuable services such as air filtering, noise reduction and recreational values in urban areas, which would not normally exist (Junge-Berberovic, R. and Graber, A., 2004).

Although it can be assumed that these added benefits would deem constructed wetlands as more socially acceptable, it is important to consider the actual thoughts and perceptions of the communities in these areas. One study on the social acceptance of ICWs was completed based on the Annesvalley project in Ireland. This study involved conducting a survey on people from farming, government, business, councils and other perspectives. Results showed that respondents found ICWs to be a social resource, bringing benefits such as amenity areas, educational facilities and enhanced landscape (Everard, M., et al., 2012).

Thus, it can be concluded, that societies are more open to the idea of constructed wetlands for the treatment of wastewater; however, it must be noted that a lack of knowledge and understanding of the social, environmental and economic benefits that these systems provide, could result in communities becoming hostile to their implementation.

2.11.4 Influence of Carbon Footprint

There is little research available on the performance of constructed wetlands in the sequestration or emission of greenhouse gases (GHG); however, natural wetlands are well known to be effective in the capture of GHGs such as CO₂. This is because wetlands are capable of sequestering carbon through high organic matter inputs and low rates of decomposition, allowing organic carbon to accumulate within the soils, and the presence of phragmites allows them to act as effective sinks of carbon and nitrogen through photosynthetic fixation (Harrington, R. and McInnes, R., (2009); Scholz, M. and Lee, B., (2005)).

When compared to traditional wastewater treatment works, constructed wetlands release around seven times less GHG emissions such as CO₂, CH₄ and N₂O (Pan, T., et al., 2011). Conversely, a study on GHG emissions from a constructed wetland treating sewage in Sweden found that plants within the constructed wetland had high respiration rates and allowed for increased emissions N₂O and CH₄, increasing GHG emissions by 71.4 tonnes of CO₂ equivalent per year (Strom, L., et al., 2007). Another study claims that constructed wetlands can emit 2-10 times more GHGs than a similar sized natural wetland (Maltais-Landry, G., et al., 2009).

Thus, although wetlands can indeed sequester and absorb CO₂, CH₄ and N₂O from the atmosphere and wastewater and use it as part of the treatment process, the subsequent GHGs that are released should also be considered. Subsequently, there are some potentially adverse effects of constructed and restored wetlands that must be considered; the GHG emissions could potentially diminish the environmental benefits of constructed wetlands as the contribution to overall carbon footprint may be greater than what they are capable of sequestering (Maltais-Landry, G., et al., (2009); O'Geen, A.T., et al., (2010)).

De Klein, J. and Van der Werf, A., (2014), Barbera, A. C., et al., (2014; 2015), Niu, C., et al., (2015), Jahangir, M., et al., (2016), and Zhao, Z., et al., (2016) have all demonstrated that the ability of constructed wetlands to sequester and/or emit GHGs is determined by the seasonal growing rate, species of vegetation which is planted and the type of media and wetland design. These studies showed clear differences between planted and unplanted systems, as well as plant species on the level of GHG emissions throughout the investigation period and found that although there were slight variations between results, overall GHG emissions were positively correlated with seasonal temperature changes.

Jahangir, M., et al., (2016) also demonstrated differences in wetland type, with horizontal, vertical, surface flow and subsurface flow systems contributing differently to GHG sequestration and emission. Others have suggested that GHG emissions are determined by the type and concentration of wastewater entering the system, with positive correlations between organic loading and CH₄ emissions identified (Corbella, C. and Puigagut, J., 2015). This would suggest that the performance of constructed wetlands in relation to GHG sequestering is subjective to the design and climatic variations associated with wetland plant performance.

In order to determine the performance of ICW's with regards to carbon footprint, it is necessary to identify how much carbon they are capable of retaining within their systems.

Once this information is acquired, it will be possible to evaluate the true contribution of ICWs in carbon reduction, and the subsequent values that this will convey.

2.11.5 Economics & Whole Life Costing

There has been little research conducted on the economic and whole life costing of either HSSF or ICW systems. However, it has been demonstrated that these systems are less expensive than traditional wastewater treatment works in terms of construction and operational costs and have even been suggested for use in developing countries due to their minimal energy, operation and maintenance requirements (Denny, P., (1997); Collins, A. R., and Gillies, N., (2014); Dimuro, J. L., et al., (2014); Vergeles, Y., et al., (2015); Wu, H., et al., (2015)).

One example where ICW's have been proven to provide a more economically viable and maintenance/labour efficient alternative to traditional wastewater treatment works (WwTW) would be the construction of a 1750pe constructed wetland in Glaslough which cost around €770,000, compared to €1.53m for a 650pe WwTW nearby (Doody, D. et al., 2009). The maintenance and operational costs of an ICW are also minimal as the system itself requires little to no energy in comparison to that of a traditional WwTW. In 2014, energy usage in Northern Ireland for all of the traditional WwTW processes and Water Treatment Plants cost around £33.4million (NIW, 2014b); hence energy efficiency reduction is an essential sustainability requirement. However, in terms of agricultural activities, one study on the economic analyses of pig manure treatment options in Ireland found that constructed wetlands were not as cost effective as land spreading, unless the farm was of large scale (Nolan, T., et al., 2012).

Other studies on the economics and whole life costing of constructed wetlands are generally based on increasing the cost efficiency of the wetlands themselves. One study investigated the cost-benefit analysis of operating an ICW treating pre-digested piggery waste at various flow rates found that there was no additional benefit to increasing rates, although this may be different at a large-scale system (Harrington, C. and Scholz, M., 2010). Although it can be assumed that constructed wetlands are more economically efficient than traditional wastewater treatment works, the lack of evidence would suggest that further research is

required to fully address the issues of whole life costing for constructed wetlands, especially in relation to the treatment of domestic waste.

2.11.6 Operational and Maintenance Requirements

HSSF and ICW systems require minimal operational requirements when compared to traditional wastewater treatment works, due to their natural design concepts and their ability to work without the need for artificial technology (US EPA, (1988); Zhang, D. Q., et al., (2014); Vergeles, Y., et al., (2015)); however, HSSF systems generally require more maintenance and operational energy costs than ICWs, as ICWs are designed to be as independent as possible (Ellis, J. B., 2003).

One of the biggest concerns with regards to the maintenance of constructed wetlands is the accumulation of organic matter over time. This accumulation of organic matter effectively determines the lifespan of the constructed wetlands, as once the surface of the ponds rises to meet the level of the embankment, the pond will no longer be effective in capturing and retaining the wastewater. Therefore, it is important that the accumulated matter is maintained at an appropriate level so as the lifespan of the wetland is increased.

It is expected that this level will not be reached within ICWs for around 50-100 years, however if the accumulated matter is removed regularly, the lifespan of the wetland will continue indefinitely (Carty, A., et al., (2008); Scholz, M., et al., (2007)). HSSF systems on the other hand are more susceptible to clogging from suspended solids if adequate removal does not occur at the settlement ponds (Vymazal, J., 2011); subsequently, it is expected that accumulated matter should be excavated between 10-15 years to ensure the lifespan does not diminish (Ellis, J. B., 2003).

Overall it is demonstrated that operational and maintenance requirements for both systems are comparatively lower than traditional wastewater treatment works. Studies are becoming more concerned with improving the operation and maintenance of constructed wetlands with many new techniques and designs being tested (Liu, R., et al., (2015); Wu, H., et al., (2015); Zhang, L., et al., (2015)). However, there is still little information available on accurate operational and maintenance costs for constructed wetlands treating domestic wastewater.

2.11.7 Climate Change Mitigation Potential

A further attribute that constructed wetlands have is their climate change mitigation potential. Their ability to withstand shock loads from flooding and cope well under seasonal variations, indicates that they have the potential to remain robust under the influences of climate change variations; however, they also bring many other benefits which aid in the reduction of the causes and effects of climate change as discussed below.

Constructed wetlands are capable of sequestering carbon, a major contributor to GHG emissions and climate change, through a number of physical and chemical processes which occur within the wetland structure (Harrington, R., and McInnes, R., (2009); Scholz, M., and Lee, B., (2005)). They have also been shown to release far less GHG emissions than traditional wastewater treatment works (Pan, T., et al., 2011).

Constructed wetlands can also be used effectively to mitigate the impacts of climate change through flood alleviation. Wetlands have repeatedly demonstrated their ability to hold and retain water for long periods of time, even under shock loadings and flooding (Jenkins, G., A., et al., 2012). This characteristic highlights how constructed wetlands can be used as a potential flood control measure, to ease the loading of high precipitation levels on nearby water courses and groundwater stores.

The Vallevecchia Wetland System in Northern Italy demonstrates this attribute very well; the system was capable of retaining water during flood periods, which was then treated and used for irrigation purposes during droughts or dry spells (Carrer, G., M. et al., 2011). Again, this illustrates how wetlands can be used to mitigate the impacts of flooding during high precipitation periods, as well as the impacts of drought.

Constructed wetlands require very little operation and maintenance, and as such, their energy consumption is minimal when compared to traditional wastewater treatment works (Zhang, D. Q., et al., (2014); Vergeles, Y., et al., (2015)). By using constructed wetlands as an alternative wastewater treatment method, less energy is required, giving the subsequent benefits of reduced fuel consumption, less emissions and reduced overall carbon footprint.

2.11.8 Summary of Appraisal Factors

Overall, it can be seen that constructed wetlands provide a number of attributes which can aid in their overall performance appraisal. However, it must be noted that there is limited research dedicated to evaluating these key issues. The performance of constructed wetlands should not be limited to their ability to treat wastewater but should consider the other contributions they provide as discussed. Thus, it is recommended that further research is conducted on these key performance indicators for constructed wetlands, so that a more thorough appraisal of their performance can be conducted.

2.12 Current Guidance for CW in Northern Ireland

Although there are many design guides available on the development of constructed wetlands the *Guidance Document for Farmyard Soiled Water and Domestic Wastewater Applications* (Carty, A., et al., 2008) is the only guidance relevant to Integrated Constructed Wetlands. It was published by the DEHLG in the Republic of Ireland in 2010 and has since been adopted for the construction of ICWs in Northern Ireland. The guidance was developed for the treatment of farm yard soiled water and domestic wastewater. It aims to provide a 'practical framework for good practice in the design, site selection, construction, and maintenance of ICWs' for 'practitioners in the field of waste water treatment, planners, policy makers and other interested parties in both public and private sectors' (DEHLG, 2010)

The guidance does not define what is meant by farm yard soiled water and domestic wastewater and both are very different in terms of properties and sources. The requirements of a farmer are different to those of a large-scale sewage treatment provider. The guidance was based on work in Southern Ireland, although no reference to locations is offered, and claims that ICWs have the potential to deliver a substantial range of ecosystem services, including flood attenuation, amenity and recreation. They can integrate the sustainable management of land, water and biological resources consistent with the ecosystem approach, to promote conservation and enhance biodiversity. Despite these claims relatively little research on the use of ICWs in terms of ecosystem services, flood attenuation, amenity and recreation has been done. Rather these potential benefits are based on research on generic wetlands development. The need of a separate design guide giving specific consideration to the requirements of a town is obvious.

The guidance document is divided into 7 chapters. Chapter 1 explains the background to the concept and processes surrounding constructed wetland development and outlines each of the steps and decisions involved in design, installation and monitoring. The introduction highlights the importance of using a sustainable method of wastewater treatment such as constructed wetlands. The design guide claims to be based on experiences from about 60 ICWs however it gives no reference to these.

Chapter 2 considers site assessment to determine the suitability of an ICW so that time and expense is not wasted. It considers whether the ICW can be developed safely in terms of construction and environmental impacts, providing baseline information for regulators, designers, and contractors. Key issues addressing social, ecological and economic considerations are given.

Chapter 3 details the process of undertaking a site assessment i.e. desk study and collation of supporting information; visual assessment; characterisation of wastewater; evaluation of receptor sensitivity and location; site tests (trial hole, soil characteristics and particle size analysis); decision process and preparation of recommendations. Example templates and information are used to explain each of these tasks.

Chapter 4 considers the need of an ICW to conform to statutory and regulatory requirements, national legislation, regulations and that full planning permission and discharge licencing is required. However, the guidance document dates from 2010 and much of the requirements are outdated. For example, the objectives of the Water Framework Directive (2015).

Chapter 5 considers the basic concept of an ICW and its design. It states that the design must be a *'deliberate attempt to implement a holistic approach to natural resource management within the context of achieving sustainable development'* (DEHLG, 2010). However, the supporting evidence is limited for treating domestic sewage.

Chapter 6 reiterates the main aspects of previous chapters and states that the design will be site specific. Chapter 7 outlines the processes and considerations involved in the operation, maintenance and monitoring of the ICW once the construction phase is complete.

Based on this critical review of current guidance in NI, the following points are made:

- The design guide is outdated.

- A guidance document based on both agricultural and domestic wastewater is not appropriate to the effective treatment of domestic sewage.
- Research is required to determine what changes are required for treatment of domestic sewage.

2.13 Critical Review of Literature

In summary, it has been demonstrated that wetland design in terms of water depth, soil depth, soil composition, surface area, wetland shape and number of ponds, all have an influence on the performance of both HSSF and ICW systems. Each of these design principles have varying impacts on either of these wetlands. For example, water depth can be more influential to the performance of ICWs than HSSF wetlands, due to their sensitivity to hydraulic flow. HSSF systems on the other hand require a greater soil depth to allow for adequate treatment processes. Thus, it can be concluded that despite differences between the two types of wetland, the design principles are highly influential to their performance and should be considered in the development process.

The hydraulic interactions within constructed wetlands are, without any doubt, significantly influential to the overall performance and efficiency of the treatment processes. Having adequate HLR and HRT are fundamental factors in ensuring the appropriate quality of effluent is reached at the outlet of the wetland system; however, there are differences in opinion as to what can be defined as 'adequate'. HLR should be high enough to allow the wastewater to flow through the system, yet low enough that it does not simply pass through too quickly for the wetland to treat. HRT must be high to ensure the wetland has enough opportunity to go through the treatment process, however, it must not go above the peak level where it begins to become inefficient in treating certain contaminants.

There is a significant impact of hydraulics on the performance and efficiency of constructed wetlands. The level of significance on each of the HLR and HRT depends greatly on various other contributing factors as discussed. It can be recommended therefore that these factors are considered when designing the constructed wetland to ensure that optimum performance is reached for the specific type and volume of wastewater being treated.

However, there are still differences in opinion as to the extent that HLR impacts on performance, the importance of HLR in relation to other contributing factors (such as hydraulic

retention time), and how HLR should be altered to optimise the performance of the wetland to enhance treatment efficiency.

Plants play a crucial role in influencing the performance of constructed wetlands for wastewater treatment due to their phytoremediation mechanisms (Figure 2.13). Not only do vegetated systems prove to be more robust and effective than non-vegetated systems, but differences in species within the same wetlands can also cause various results. Therefore, it is important that the appropriate species is selected for use in a specific wetland depending on their ability to cope with different types of wastewaters under various climatic conditions.

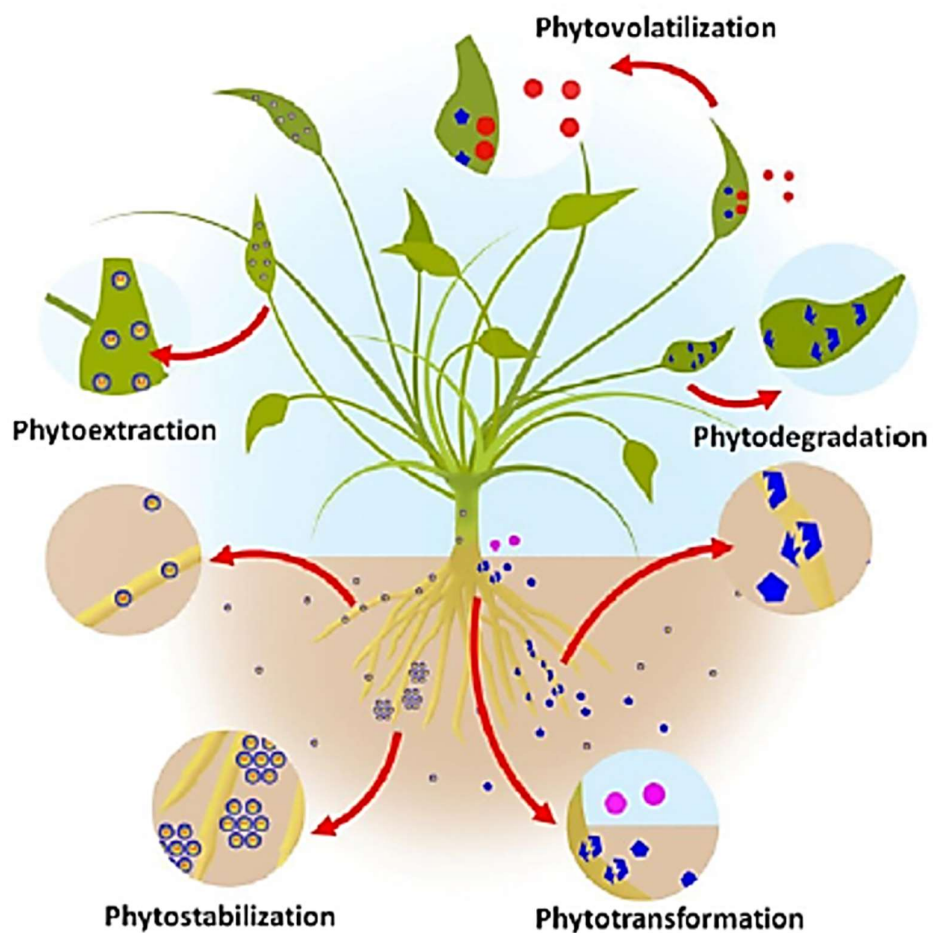


Figure 2.13 Phytoremediation mechanisms within wetland plants (Parmar, S. and Singh, V., 2015)

The performance of constructed wetlands can be appraised on factors other than their ability to treat wastewater. Secondary issues such as land use, odour, social impact, carbon footprint, economic value, operation & maintenance costs and climate change mitigation potential, each all contribute to the overall value of constructed wetlands. However, there is limited research available on these issues resulting in a lack of understanding of the true contributions of constructed wetlands.

In conclusion, this review has considered relevant literature relating to Constructed Wetlands, in particular ICW and HSSF systems. The following areas of research have been identified:

- Wetland design, location and climatic conditions influence the performance of both HSSF and ICW systems. However, each factor has varying impact. An appropriate design must be used in a specific wetland to ensure that optimum results can be achieved. Research into the hydraulic and environmental design principles of Stoneyford ICW is required.
- Both HSSF and ICW systems are able to treat various types of contaminants. However, there are contradictions in the literature relating to how they perform under shock loadings, seasonal variations and wetland maturity. Research into these factors is required at Stoneyford ICW.
- HLR and HRT are fundamental factors. However there are differences in the literature relating to optimum performance. Research is required for Stoneyford ICW.
- Drones are now being used for applications that were previously considered difficult or impossible. Their use should be evaluated to determine what new types of information can be derived from Stoneyford ICW.
- A lack of appropriate guidance documents within the UK and Ireland has also been identified, with none relating to the specific use of ICWs for domestic wastewater alone. Thus, it is recommended that further research is carried out to develop the background knowledge and understanding required for an appropriate guidance document for integrated constructed wetlands treating domestic wastewater in Northern Ireland.

CHAPTER 3. STONEYFORD ICW AND TEST RIG DEVELOPMENT

3.1 Introduction

This chapter describes development of Stoneyford ICW from site selection, the planning process, construction, commissioning through to operation and maintenance. It helps to illustrate the processes involved in development of an ICW. This chapter also considers the design, construction and operation of the small-scale Test Rig that allowed the smaller scale research investigations detailed in this thesis.

3.2 Background to the Stoneyford ICW Development

Stoneyford ICW was commissioned by Northern Ireland Water (NIW) to replace an existing Waste Water Treatment Works (WwTW) that had been servicing the village of Stoneyford since 1980. The ICW was designed by VESI Environmental and built by BSG Civil Engineering. The Stoneyford WwTW had been originally sized for 331 PE. It was upgraded in 2001 to allow for inlet screening and aeration facilities increasing its capacity to 695 PE. Due to the growth of Stoneyford village the WwTW became overloaded increasing operational and maintenance costs.

It became apparent to NIW that the existing WwTW system would need to be replaced by a larger works. However, stricter NIEA water quality standards meant that more complex and expensive treatment processes would have to be incorporated with the new facilities costing an estimated £1.4 million. This was substantially higher than the estimated capital cost to construct an ICW at Stoneyford at approximately £800,000, excluding maintenance and NIEA licensing.

This prompted consideration of an ICW as an alternative method to treat wastewater at Stoneyford similar to the ICW systems being pioneered by the National Parks and Wildlife Service, Department of Environment, Heritage and Local Government at sites across Southern Ireland. Visits were made to sites such as Glaslough by NIW. Following a NIW consultation with stakeholders and an economic appraisal it was proposed that an ICW at Stoneyford was the preferred solution.

An ICW at Stoneyford would provide improved wastewater treatment for the existing population and future development of the village as well as creating an aesthetically pleasing area that is rich in biodiversity with recreational potential.

Both NIEA and the NIW regulator agreed that the Stoneyford ICW should act as the first full-scale trial in Northern Ireland for a period of at least 5 years to determine whether it was a viable solution for upgrading other WwTWs in Northern Ireland. The full-scale trial could be benchmarked against similar sized WwTWs by NIW with similar consent standards to establish an appraisal between key measures such as capital costs, compliance with consent conditions (quality and volumetric conditions), operating costs including labour, power, materials, sludge treatment and disposal, environmental issues, and reliability (breakdowns, loss of process, call-outs).

The following timeline provides a brief summary of the stages involved in the Stoneyford ICW and test rig.

1. NIW Stakeholder liaison August 2013;
2. Public information events held by NIW from August 2013 to June 2014;
3. Planning application submitted by NIW in August 2013;
4. Planning permission granted to NIW in April 2014;
5. Construction starts April 2014;
6. Planting of ponds from July 2014 to September 2014;
7. Diversion of existing flows of domestic waste to ICW in November 2014;
8. Site completion by February 2015;
9. Agreed justification and design for Test Rig March 2015;
10. Construction of Test Rig commenced August 2015;
11. Test Rig planted (7 of 8 beds) January 2016;
12. Test Rig completed July 2016.

3.3 Stoneyford ICW Site Selection

Site selection for Stoneyford ICW had to comply with the same guidelines for selection of a traditional WwTW site, including those of NIW Environmental Management System (EMS) and Planning Service Designations. If these guidelines are met an ICW can be built almost anywhere using the existing landscape to shape the land surface and seal the basin to retain the water. However, due to the holistic approach of ICWs to enhance the natural landscape and biodiversity, some sites are better suited than others with a good site containing the following:

- convenient location to the wastewater source,
- good local infrastructure and access,
- adequate area and land availability,
- level or gently sloping land,
- heavy soils with low permeability,
- not in an area of high flood risk/flood plain,
- no issue with environmental sensitivity,
- rural area preferred to mitigate potential impacts of odour.

A potential site was selected to the north east of Stoneyford village. A site investigation was required to determine the soil permeability at the required depth, groundwater level, aquifer classification, groundwater vulnerability and groundwater response matrix. The designers employed by NIW were VESI Environmental. They had to consider effluent quality and quantity, location, landscape, geology, hydrology, soils and economics.

Factors such as influent composition, hydraulic retention time, and site characteristics are fundamental in calculating the area and form of the ICW. Initial investigations identified an area north east of Stoneyford as a suitable site for the construction and operation of an ICW as the ground was generally sloping with adequate area necessary for the development and construction process. The suitability of the site was then further assessed through more investigative site visits and desk studies and results concluded that the site was suitable for the construction and operation of an ICW. Figure 3.1 shows the proposed Stoneyford ICW site before construction.



Figure 3.1 Stoneyford site before construction.

3.4 Stoneyford ICW Planning and Design

The treatment system was designed by VESI Environmental and consultation with Dr. Rory Harrington to treat domestic wastewater for a capacity in excess of 950 PE and consists of 2 settlement ponds, 5 treatment ponds, a control building, site access road, boundary planting and landscaping, and monitoring equipment such as samplers and flow meters.

The ICW pond surface area was determined using the DEHLG 2010 design guide recommendation that the area should be between $20\text{m}^2 - 40\text{m}^2$ per population equivalent (Carty, A., et al., 2008). To ensure the sustainability of the ICW in terms of future development in Stoneyford village, the wetland area for the site was designed to provide treatment for a PE of up to 950, with an overall area of approximately $38,000\text{m}^2$.

The approximate area of the wetland site is 8 hectares, allowing for access roads, car parking and landscaped areas. Details of each pond and their corresponding areas are shown in Table 3.1.

Table 3.1 Individual pond areas of Stoneyford ICW.

Pond number	Pond area
Pond 1	7,476 m ²
Pond 2	8,301 m ²
Pond 3	8,939 m ²
Pond 4	5,874m ²
Pond 5	6,479m ²
Settlement Pond A (SPA)	300 m ²
Settlement Pond B (SPB)	240 m ²

Figure 3.2 shows the proposed layout for Stoneyford ICW located just to the east of Stoneyford village. This shows the ICW site located beside the Stoneyford River. The effluent is pumped to the two sludge ponds located to the east. The effluent then flows sequentially through the series of 5 treatment ponds before being discharged into the river to the west. The proposed layout also shows access roads and walkways around the ponds. Two settlement ponds were proposed so they could be alternated to allow for desludging without interrupting the treatment process as seen at Glaslough (Dong, Y., et al., 2011)

The operational water depth of each treatment pond is between 150mm - 200mm, with a maximum depth of 300mm. The pond embankments are sloped with a gradient of 1:1.5 - 1:2 and the upper embankments are a minimum of 3m wide to allow for access and maintenance. The ponds are connected using 150mm diameter pipes which are placed on the wetland floor. Water levels can be managed within each pond using adjustable weirs which are placed on the outlet pipe of each pond.

The original design included purpose built concrete weirs to control the water level within each pond. This included automatic data recording of wastewater flow rate at the outlet of each pond using a SCADA flow monitoring system. An automatic sampler was positioned on the weir to obtain wastewater samples for routine analysis.

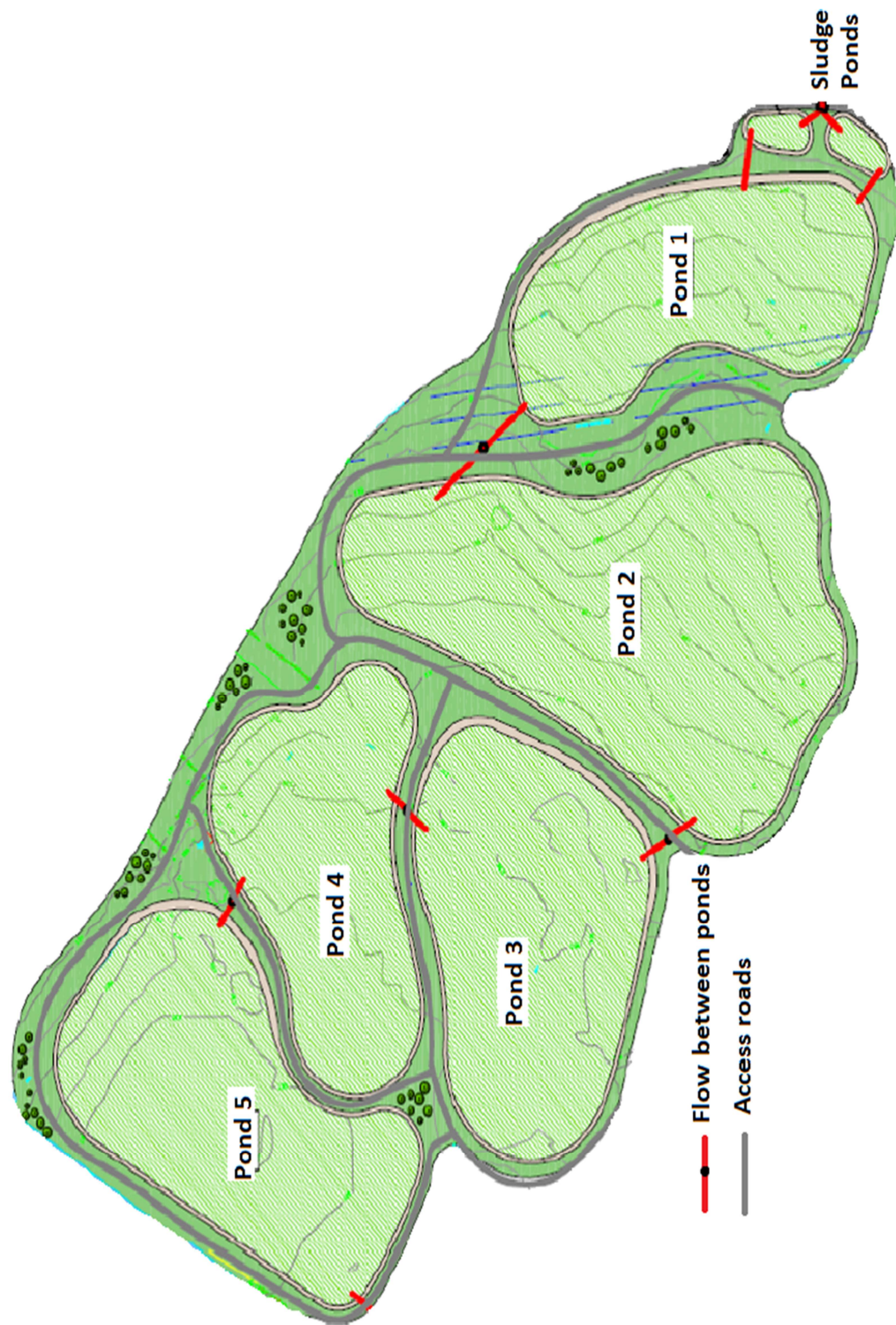


Figure 3.2 Proposed Stoneyford ICW layout drawing (derived from drawing by BSG Civil Engineering).

3.5 Construction and Planting of Stoneyford ICW

The construction of Stoneyford ICW started in April 2014. The main construction works involved 9 stages. Figure 3.1 shows the ICW site before construction. Figure 3.3 shows the site at Stage 5 with some water lying in the floor of each pond.

- **Stage 1:** Stripping of topsoil from site and retained for later use;
- **Stage 2:** Excavation of sub-soil and creation of temporary embankments;
- **Stage 3:** Layering and compaction of soil to create a base for each pond;
- **Stage 4:** Creation of embankments;
- **Stage 5:** Re-distribution of top-soil over the base of each pond for planting as shown in Figure 3.3;
- **Stage 6:** Pipe laying and ducting between ponds;
- **Stage 7:** Placement of stones/chippings beneath inlet and outlet pipes to prevent erosion;
- **Stage 8:** Planting each pond with emergent vegetation as shown in Figure 3.4;
- **Stage 9:** Ponds allowed to flood to design water depth as shown in Figure 3.5.



Figure 3.3 Stages 1 – 5 Developing the pond layout.



Figure 3.4 Pond 1 planted with emergent vegetation July 2014.



Figure 3.5 Flooded ICW.

A Control Building was constructed beside the car park south west of the ICW. This included the Stoneyford ICW weather station. Figure 3.6 shows some of the weather measurement equipment attached to the Control Building. Weather data was display and recorded within the Control Building continually on a 30 day loop.



Figure 3.6 Stoneyford ICW weather station on Control Building.

Continuous flow monitoring of the influent and effluent was proposed in the original design using automatic flow monitoring equipment. Flow monitoring took place within the specifically designed chambers as shown in Figure 3.7. The concrete chambers for all ponds were created using pre-cast sections so they were all of the same dimensions. The monitoring equipment recorded daily flow rate at the inlet and final outlet of the ICW with average rates noted. The flow rates were also recorded within the Control Building.






Figure 3.7 Concrete Flow Chamber between ponds.

Due to the proximity of Stoneyford River, risk mitigation measures were in place throughout construction of the ICW to limit the potential impact on adjacent surface water and groundwater environments. The following measures helped to ensure that there were no adverse impacts on groundwater caused by infiltration:

- Shallow water depths within each pond (<300mm);
- Low hydraulic pressure;
- The presence of organic matter in the soil;
- Compaction of soils to form a soil liner with a low permeability ($>1 \times 10^{-8} \text{m/s}$). (SIC)

Table 3.2 Main species planted in Stoneyford ICW (VESI, 2014).

Botanical name	Common name	Flowering period	Max height (m)	Max water depth (mm)	Summer Picture	Winter Picture
<i>Glyceria maxima</i>	Reed sweet grass	Jun – Aug	2.5	600		
<i>Carex riparia</i>	Common sedge	May – Jun	1.5	300		
<i>Typha latifolia</i>	Reed mace	Jun – Aug	2.5	100-800		
<i>Iris pseudacorus</i>	Yellow flag iris	May – Jun	1	200		Deciduous Not visible in winter
<i>Typha angustifolia</i>	Small reed mace	Jun - Jul	3	150		

Planting involved emergent species within each wetland pond and tree species along the embankments of the site. The original surrounding trees had to be removed to prevent shading and penetration of roots into the ICW. The ponds were planted with approximately 60,000 emergent wetland species similar to those used at Glaslough (Dong, Y., et al., (2011; 2012); Kayranli, M., et al., (2009)). The plant species planted at Stoneyford as recommended by VESI are shown in Table 3.2. This shows the expected height of each plant species and the recommended water depth in which it should be planted. Images of what each of the plant species look like in summer and winter are also shown.

In order to keep within the objectives of an ICW the development should enhance the existing habitat and biodiversity value of the site. The Stoneyford ICW site was landscaped to maximise the potential for wildlife habitat creation and enhancement. Landscaping including planting of willow trees for use as a possible renewable energy source as seen in Figure 3.8.



Figure 3.8 Planting of willow for landscaping.

During the construction phase a number of issues arose which impacted progression of the development and site works.

- **Poor weather conditions** – prolonged spells of wet weather during the construction phase made on site conditions unfavourable for site works causing delays in completion.

- **Late planting of ponds** – as a result of the poor weather conditions and delayed construction of the ponds, the planting began in July which was occurred later than proposed, giving plants little time to establish themselves before winter months approached.
- **Cattle in ponds** – cattle from nearby fields entered the site during the construction phase after breaking through temporary fencing and walked through the unflooded ponds (Figure 3.9).
- **Vandalism** – vandalism on site caused damage to the automatic samplers and fencing. As a result, the automatic samplers were not used and weekly manual samples (grab samples) were taken instead.



Figure 3.9 Cattle on site after breaking through temporary fencing.

The proposed finish date for Stoneyford ICW was February 2015. After dealing with these issues the construction was completed and commissioned with first water quality testing beginning in December 2015.

3.6 Stoneyford ICW Operation and Maintenance

Integrated constructed wetlands are designed to be as self-maintaining and as self-operable as possible. However, an operation and maintenance plan had to be developed by NIW to ensure adequate procedures were implemented on an on-going basis. The proposed main maintenance procedures have been listed below for the ICW at Stoneyford:

- Water level management and flow maintenance;
- Flow monitoring to and from the wetland;
- Monitoring surface water quality;
- Monitoring of receiving surface water quality;
- Vegetation monitoring;
- Maintenance of access;
- Maintenance of inlet and outlet pipes;
- Maintenance of embankments;
- Sediment/sludge management;
- Tree maintenance.

Sludge removal is not carried out on a continuous basis for an ICW. Instead the sludge is allowed to accumulate in the sludge ponds for a number of years until it has to be removed. The sludge should then be caked sufficiently to be removed via lorry where it is likely that NIW would dispose of this sludge at the Duncrue incineration site.

A visual inspection of the water levels in each pond was proposed weekly to ensure that water depths are no greater than 300mm and are maintained at approximately 200mm. A visual inspection of the sloping embankments on either side of the pond (internal and external) is required to check for any sign of leakage, slippage or distortion. Any defects noted should be recorded and necessary action undertaken immediately. All inlet and outlet pipes within the ICW system should be visually inspected for blockages, sediment accumulation, vegetation growth around the pipe and debris.

The main growing season is during spring and summer with some plants starting to die back in autumn. Some species are semi-evergreen whereby the level of dieback will depend on the winter while evergreen plants will brown slightly and reduce in height during the winter. Any differences in the composition or cover of the plants should be noted and recorded weekly.

The general appearance of the receiving waters (Stoneyford River) should be noted, paying particular attention to water colour and for any excess foaming where the pipe from the ICW enters the river. The temperature and pH of the influent and final effluent was proposed to be monitored weekly.

It was proposed in the initial design that a sample of the influent into the ICW, the outlet of all treatment ponds and the final effluent from Pond 5 should be taken monthly and analysed for the following parameters: conductivity, BOD, COD, suspended solids, total nitrogen, nitrates, total phosphorus, total coliforms, faecal coliforms (E. Coli), nitrites, ammonia, sulphate, phenols, oils, fats, greases, and metals. The sampling was to occur using an automatic sampler which would be collected by a site operator and taken to the NIW laboratory at Altnagelvin. This was later modified to sampling at all of these locations once per week.

The Stoneyford River should also be sampled at the ICW discharge point quarterly to monitor the following parameters: pH, dissolved oxygen, BOD, total nitrogen, ammonia, colour, and odour.

Over the design life of the ICW there would be expected to be an accumulation of sediment. This would be confined initially to the sludge ponds. It is expected that as the ICW develops sediment may accumulate within the 5 main ponds. If deemed to be a problem, the depth of sediment should be investigated before removal to ensure that the compacted soil layer beneath the sediment is not disturbed. Ideally the material that lies 100mm above the soil layer base of the ICW should be undisturbed.

The proposed design specified that rough cut grass areas should be maintained to achieve an even cover of longer vegetation and to control weeds. This would prevent contamination of the planted pond species.

3.7 Test Rig Planning and Design

The small-scale Test Rig (TR) consists of 8 test beds. Seven test beds are based on the design principles of an ICW and one bed designed on the principles of a Horizontal Sub-Surface Flow constructed wetland (HSSF). The 7 ICW test beds allowed for the study of the effects of varying influent volume similar to the research investigations carried out by Harrington, C., and Scholz, M., (2011). The HSSF allowed comparison with the ICW.

Consultation with NIW concluded that the best position for the TR would be within the boundaries of Pond 1. This would allow for adequate area for construction of the TR and gravitational inlet flow from the sludge ponds. This would not disrupt treatment of the rest of the ICW as the outlet from the TR test beds would flow into Pond 1 to continue with treatment as normal. This also ensured that the original ICW boundaries remained and no additional land take was required. There would be minimal impact on the existing landscape and biodiversity.

The design for the Test Rig is based on principles of being able to test 3 different surface areas per person equivalent (SA/pe) of 20m², 30m² and 40m² against various water depths (Dw) between 50mm and 250mm. Previous studies had suggested that the plant beds should be constructed at a Width: Length ratio (W:L) of 1:2 to gain optimum hydraulic retention and influent mixing (Carty, A., et al., (2008); Scholz, M., et al., (2007)). To test the effect of surface area (SA) and Dw on retention time the W:L ratio for each of the test beds should remain constant and sized accordingly.

The DEHLG design guide (Carty, A., et al., 2008) states that the surface area of an ICW should be between 20m² – 40m² for one person. In order to test the proposed design SA of 20-40m² per person equivalent it was important that there was a test bed to represent each of the sizes 20m²/pe, 30m²/pe and 40m²/pe. The scaling of each test bed was increased to a SA of 2pe giving the test beds SAs of 40m², 60m² and 80m². The W: L ratio was maintained at 1:2. The dimensions of each test bed are shown in Table 3.3.

Table 3.3 Test Rig Test Bed dimensions.

Test Bed Type	Test Bed Number	Surface Area	Test Bed Width	Test Bed Length
ICW	1, 7	40m ²	4.475m	8.95m
	2, 6	60m ²	5.47m	10.95m
	3, 4, 5	80m ²	6.32m	12.65m
HSSF	8	10m ²	2.24m	4.47m

The design for the HSSF Test Bed is based on a simple 1 pond system at the recommended surface area of 5m²/pe (Vymazal, J., 2005). In order to have the same scaling factor as the ICW Test Ponds of 2pe to allow for appropriate comparison to be made, the total surface area of

the HSSF is 10m². The W: L ratio is also recommended at 1:2 giving the HSSF dimensions of 2.24m x 4.47m.

The proposed design drawing of the TR layout is shown in Figure 3.10. The influent from the sludge ponds is divided equally across all test beds using a 10 way splitter chamber (Figure 3.11). Chamber 3 to 10 allows each of the 8 test beds to gain equal flow and volumes of wastewater. Chambers 1 and 2 were bypassed directly into Pond 1.

The rate of influent flowing into the ICW is dependent upon the rate of usage within the local community and cannot be altered within a live treatment system. After consultation with NIW and CAST members, it was decided that the volume of the test beds would be varied by way of a combination of surface area (SA) and water depth (Dw).

Varying the depth of soil (Ds) in the test bed was considered. However, as it would not be practical to alter the soil depth of an ICW, it was decided that the soil depth would remain constant at approximately 200mm to be representative of the full-scale treatment system. The proposed depth of the 7 Test Rig ICW beds is a total of 600mm which allowed for 200mm soil depth for planting and up to 300mm water depth for testing, with a 100mm surplus to prevent overflow.

The water depth of T8 HSSF bed was varied by altering the level of the outlet pipe. The different levels of Dw investigated in the HSSF bed can be seen in Table 3.4. The total depth of T8 was 500mm. The soil: gravel ratio was 300mm: 200mm which allows adequate depths of soil for plant rooting as well as enough gravel depth to prevent clogging.

Table 3.4 Test Rig HSSF water levels.

Water Depth (mm)	Soil/Gravel Depth (mm)	Difference of water level from soil surface (mm)
300	500	-200
400	500	-100
500	500	0

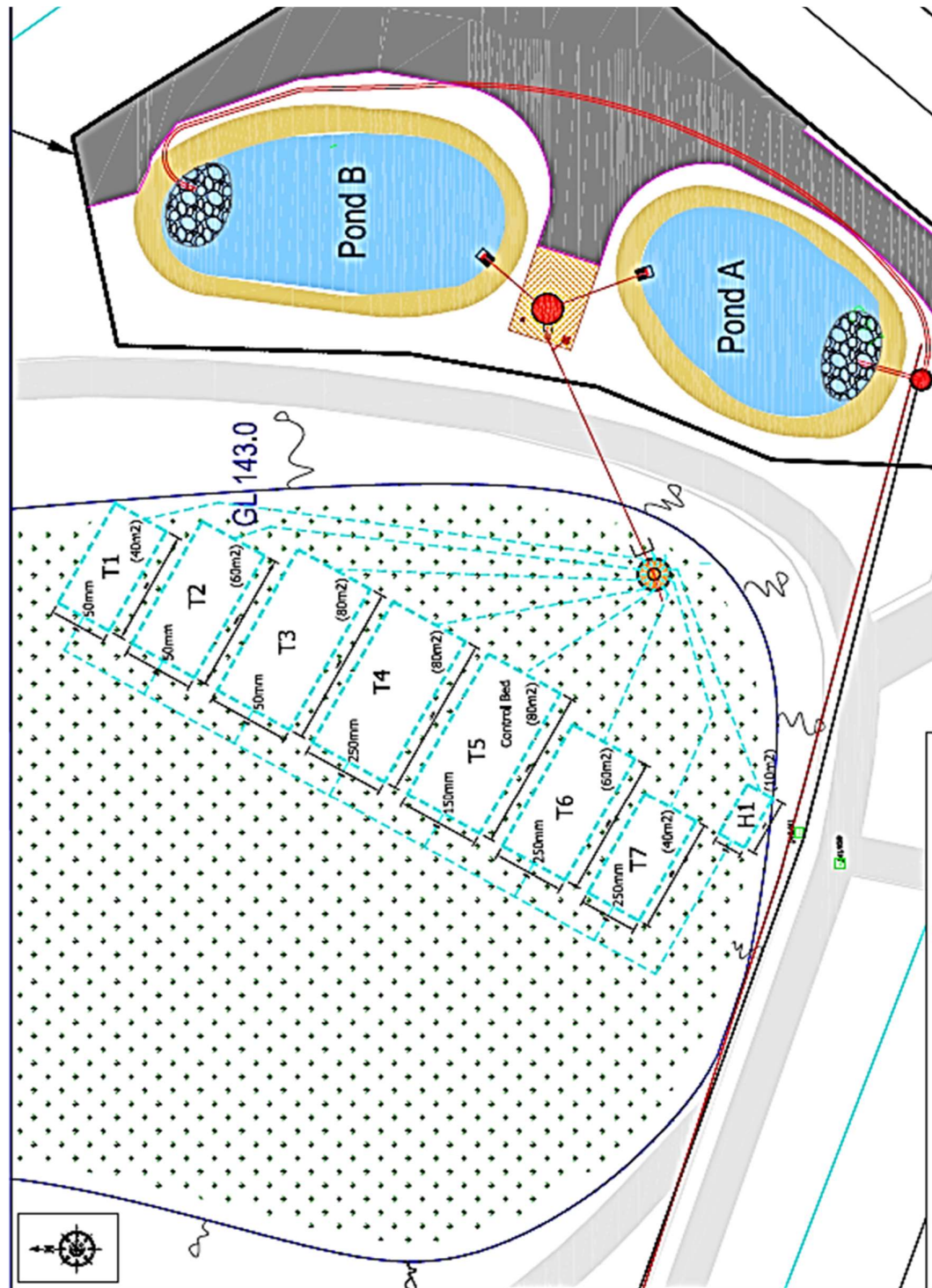


Figure 3.10 Proposed TR Layout within Pond 1 (Drawing by BSG Civil Engineering).

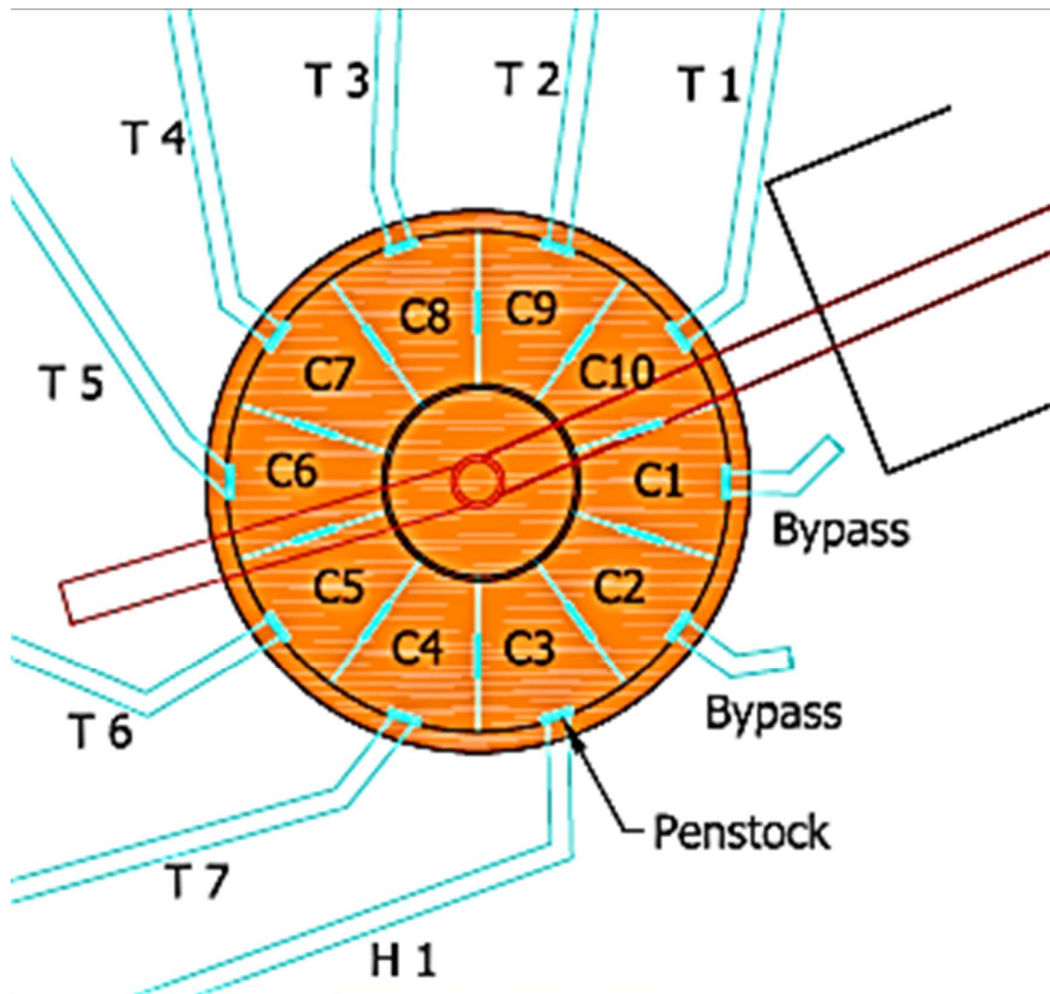


Figure 3.11 The 10 Way Splitter Chamber (Drawing by BSG Civil Engineering).

The small-scale Test Rig was constructed in Pond 1 of the ICW. The vegetation was removed and a bund formed. Soil was imported and levelled to form a platform (Figures 3.12). The test beds were dug into this soil platform and lined with timber and plastic (Figure 3.13). The 10-way concrete splitter chamber (Figure 3.11) was positioned and connected to the original inlet into Pond 1. Piping for each test bed was installed and checked for leakages (Figure 3.14). Crushed rock was used to create access paths around each of the beds for sampling and monitoring.



Figure 3.12 Importing of soil to create a platform for the TR construction.



Figure 3.13 Construction of timber framed Test Beds.



Figure 3.14 Checking the TR for leakages and flow.

The test beds were filled to the required depth with soil from the ICW site. Although gravel was in the proposed design crushed rock was used to fill the HSSF test bed due to availability (Figure 3.15). All 8 test beds were planted with *Glyceria maxima* (Figure 3.16 and 3.17). *Glyceria maxima* was planted to allow for faster establishment of the test beds so testing could begin sooner (Harrington, C., et al., 2011).

A concrete flagstone was placed below the inlet pipes of each test bed to prevent de-sedimentation. Wastewater flow from sludge pond A/B was then re-diverted to the splitter chamber to be distributed evenly amongst each of the test beds.



Figure 3.15 Filling of HSSF with crushed rock.



Figure 3.16 Planting of TR after construction.



Figure 3.17 TR Completed and ready for testing.

Similar risk mitigation measures were put in place throughout construction of the TR to limit impact on adjacent surface water and groundwater environments. A number of issues occurred during construction of the TR. Prolonged spells of wet weather caused delays. There were problems with unscreened wastewater entering the TR. This caused blockages and debris build up within the splitter chamber and test beds (Figure 3.18).

The proposed finish date for the Stoneyford TR was August 2015. After dealing with the ICW issues, construction of the TR commenced in August 2015 and ongoing delays meant the TR was not completed and commissioned until July 2016 with first sample testing beginning in August 2016.

The Test Rig was designed to be as self-maintaining and as self-operable as possible. The operation and maintenance plan for the full-scale ICW was modified for the small-scale TR. This covered the following:

- Water level management and flow maintenance.
- Flow monitoring to and from each test bed.
- Monitoring water quality of the influent and effluent of each test bed.

- Monitoring of splitter chamber and cleaning of debris build up.
- Vegetation monitoring within each test bed.
- Maintenance of access around each test bed.
- Maintenance of inlet and outlet pipes.
- Maintenance of embankments and fencing.



Figure 3.18 Debris within splitter chamber causing uneven flow.

CHAPTER 4. METHODS

4.1 Introduction

This chapter details the methods used in this thesis. The methods used to conduct a stakeholder engagement. The methods used collect data from the full-scale Stoneyford ICW and the small-scale test rig are detailed. Methods used to monitor vegetation within the ICW using a DJI Phantom 4 Drone are discussed.

4.2 Stakeholder Engagement Methods

Research has shown that incorporating stakeholder engagement into the process of data collection and knowledge development provides mutual benefits for both academic researchers and the non-academic utilisers of the information (Phillipson, J., et al., 2012). It has also been demonstrated that engaging stakeholders allows for the better adaption of the project to meet the needs of those who are most likely to put the research into practice (Reed, M.S., et al., 2014).

Stakeholder engagement allows the attitudes, opinions or perceptions towards an issue to be developed through free and open discussions between members of the group (Kumar, R., 2014). There may be downsides that some people may be uncomfortable in a group setting and too nervous to speak. Not everyone may contribute or others may influence an individual's views. Advantages of being able to receive a wide range of responses in one meeting where members can ask questions of each other were deemed to outweigh the disadvantages in relation to the overall objectives of this research (Dawson, C., 2009).

The Stoneyford ICW stakeholder engagement took the form of a focus group with a similar aim of Everard, M, et al., (2012) to ask structured questions to experts from a wide spectrum, including industry, contractors, environmentalists, engineers, academics, consultants, and planning advisors. Unlike Everard, M., et al., (2012) who conducted individual interviews, the Stoneyford meeting was designed to allow for open discussions and dialogue between key professionals.

Selection of the Stoneyford ICW stakeholders was based on their ability to contribute professional and honest knowledge and opinions on the issues surrounding constructed wetlands using a life cycle approach so a whole life understanding could be represented.

The engagement consisted of 11 stakeholders (2 academics, 2 representatives from NIW, 5 consultants, 1 Rivers Agency representative and 1 contractor). It took place at Ulster University in November 2015 for 3 hours. A PowerPoint presentation by the author gave a background to the joint research with NIW and a basic introduction to ICWs.

A week before the stakeholder engagement the invited stakeholders were sent a 'Stakeholder Engagement Brief: Integrated Constructed Wetlands' as shown within the Stakeholder Engagement Feedback Booklet in Appendix A. This provided them with a summary of the concept behind constructed wetlands and gave the aim and objectives of the engagement meeting. It also allowed stakeholders to prepare and identify any thoughts or queries that they felt could be addressed during the engagement.

At the start of the stakeholder engagement they were presented with a Feedback Booklet (see Appendix A) which contained a copy of the brief they had previously received and a list of open questions to gain their attitudes and opinions. The questions were designed to achieve 7 objectives:

Objective 1: Develop an understanding of the attitudes and opinions of key stakeholders on ICWs as an alternative to traditional wastewater treatment works;

Objective 2: Identify how the use of ICWs as a wastewater treatment method is perceived by stakeholders from various backgrounds;

Objective 3: Develop a perception of how stakeholders relate ICWs to current EU policy frameworks and sustainable development objectives;

Objective 4: Identify key variables that impact on ICW performance and establish a weighting of significance;

Objective 5: Identify key appraisal contexts of ICW installations and establish a weighting of significance;

Objective 6: Develop an understanding of how stakeholders envisage future ICW application;

Objective 7: Gain an understanding of stakeholder attitudes towards an ICW Best Practice Guidance Document.

The objectives, their subsequent discussion points and the appropriate question for each of the objectives have been summarised in Table 4.1.

Table 4.1 Stakeholder Engagement discussion points and questions.

Objective	Discussion Point	Question / Feedback Points
1	Knowledge of ICWs and their relevance to and context within Policy Frameworks and Sustainable Development Objectives	Please detail your current knowledge of ICWs, including their relevance to and context within Policy Frameworks and Sustainable Development Objectives
2		
3		
4a	Identification of the listed variables which are deemed to be significant to influencing overall ICW performance	Based on your previous knowledge and today's presentation can you identify the key variables which impact overall ICW performance?
4b	Weighting of the listed variables in order of significance to influencing performance	Can you now weight the agreed variables in order of significance to influencing performance using the pyramid below?
5a	Identification of appraisal contexts deemed to be significant in the performance evaluation of ICWs	Based on your previous knowledge and today's presentation can you identify the key performance criteria for overall ICW appraisal?
5b	Weighting of the listed variables in order of priority for further study	Can you now weight the agreed criteria in order of significance to overall ICW performance appraisal?
6	Opinions on the future of ICWs in terms of implementation and additional/alternative applications	What is your opinion on the future of ICWs in terms of implementation and additional/alternative applications?
7	Opinions and comments for an ICW 'Best Practice' Design Guide to develop an applied document applicable to various industries and applications	What are your opinions on an ICW Best Practice Design Guide to develop a document applicable to various industries and applications; What key elements should be included within the document?

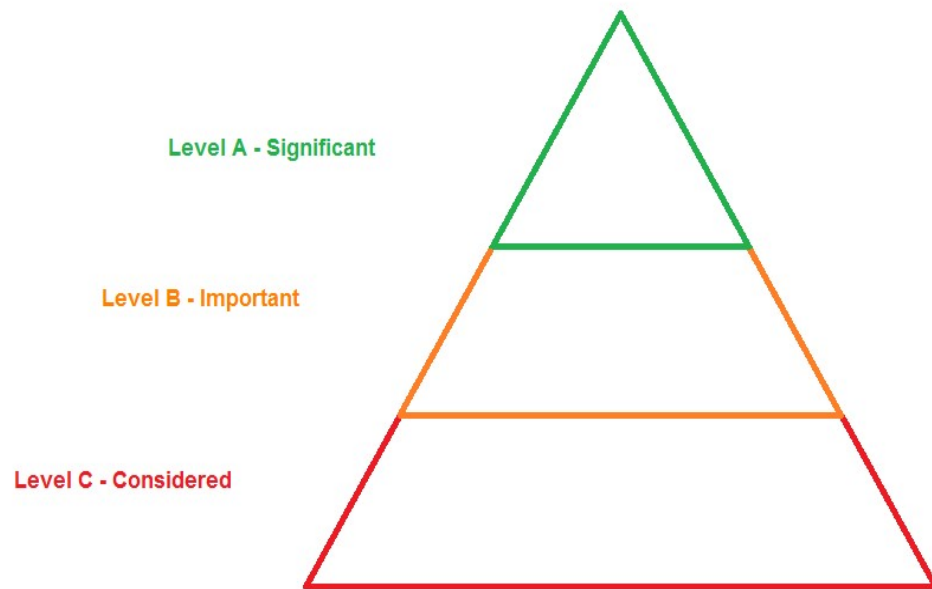


Figure 4.1 Pyramid of Significance template.

For the questions relating to weighting the variables and performance criteria, stakeholders were asked to use the pyramid template shown in Figure 4.1. The pyramid was divided into the 3 Levels of Significance as defined within the Feedback Booklet depending on the impact each factor had on the performance of ICWs. Once the stakeholders had voiced their opinions and weighted the factors they were then shown the Pyramids of Significance shown in Figures 4.2 and 4.3.

These Pyramids of Significance are based on a review of 375 articles related to constructed wetlands as listed within the References and Bibliography. Figure 4.4 shows the number of reviewed references relating to key issues that impact performance. Figure 4.5 relates to the number of references related to key factors that determine wetland performance.

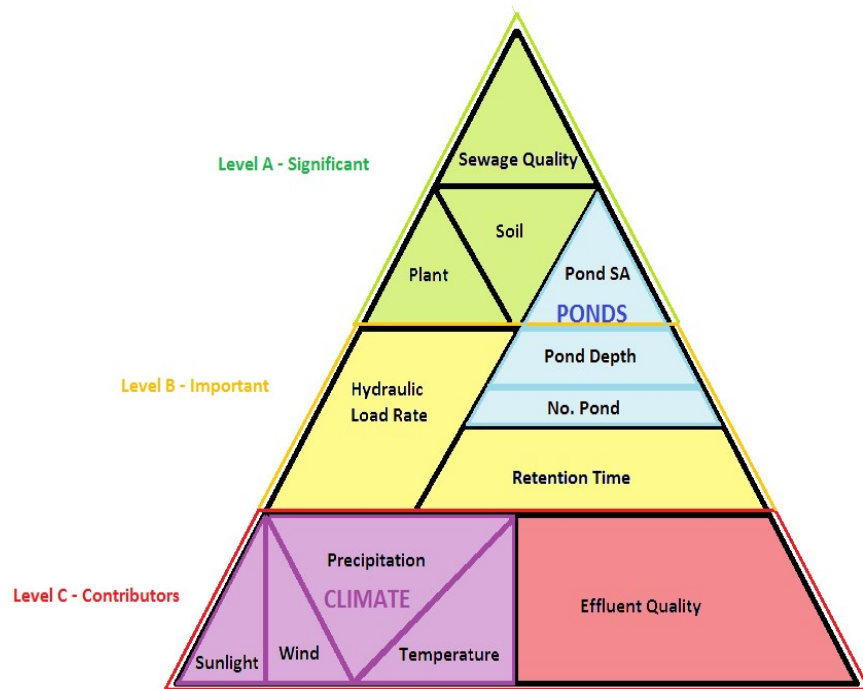


Figure 4.2 Pyramid of Significance Key Variables based on literature.

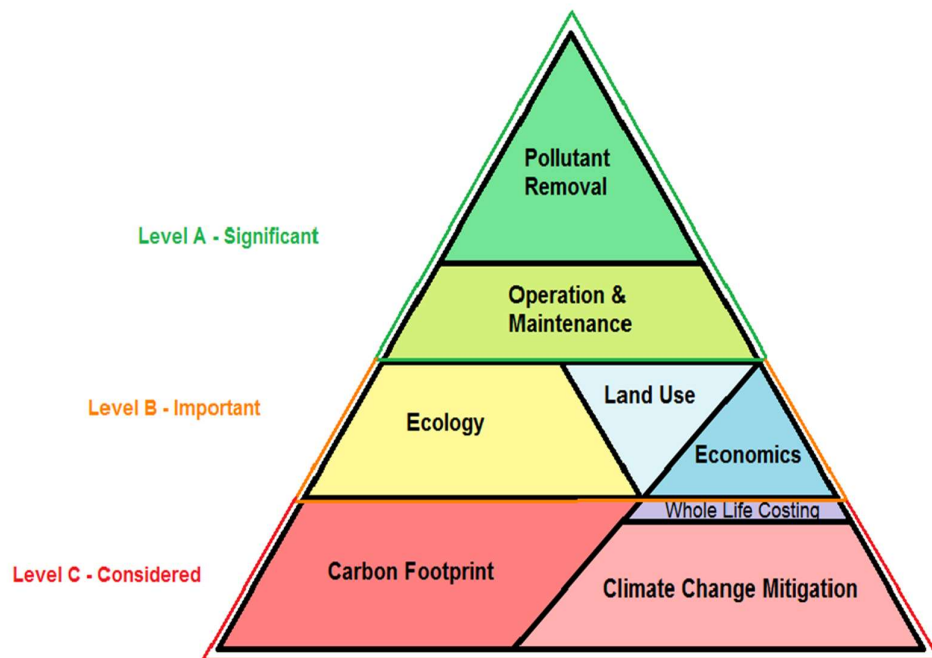


Figure 4.3 Pyramid of Significance Appraisal Contexts based on literature.

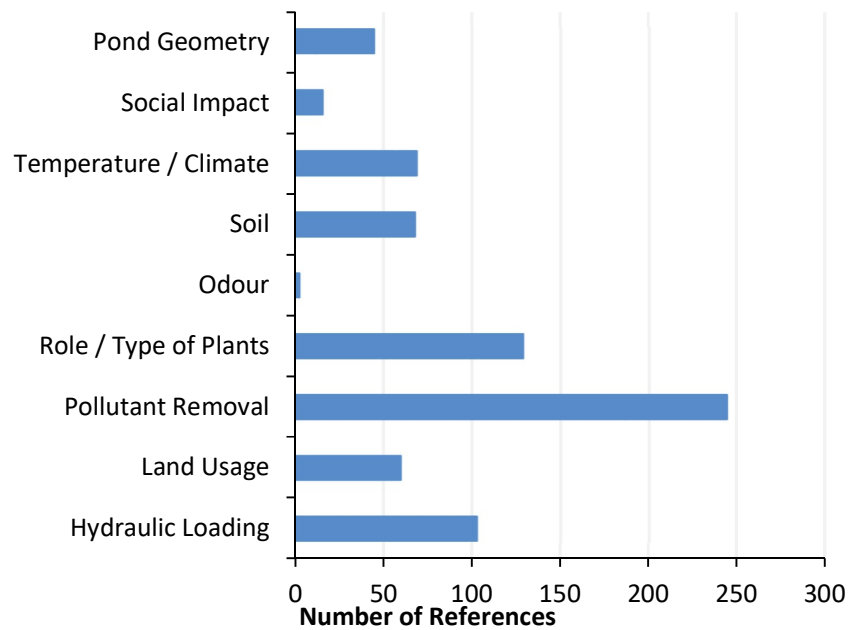


Figure 4.4 Number of references relating to key Issues.

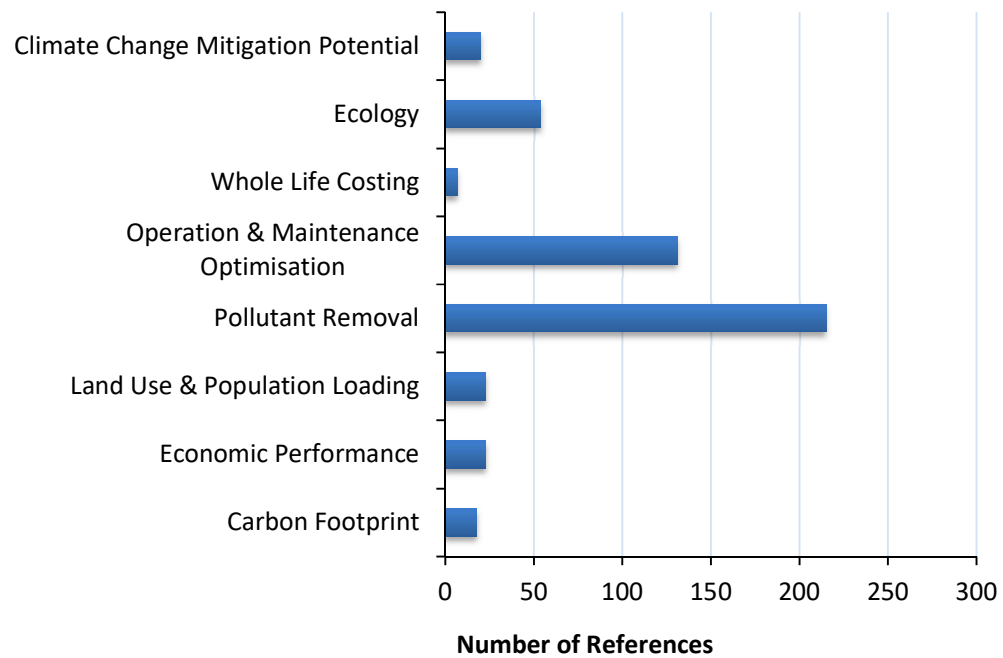


Figure 4.5 Number of references relating to appraisal contexts.

This part of the knowledge exchange was left until after the stakeholders had written and discussed their weighting of variables and contexts based on their own knowledge and understanding. This was to ensure that stakeholders' comments were based completely on their own perceptions and opinions and remained uninfluenced by what they may have believed from known literature studies and experience. This allowed the stakeholder engagement session to remain the exchange of knowledge between key professionals and provide qualitative data.

The final section of the feedback booklet allowed the stakeholders to record their opinions and comments of the stakeholder engagement process. The session was audio recorded so that an accurate account of the discussions could be documented. A transcript was then typed up which could be combined with the written record of stakeholder comments from the Feedback Book to aid the production of anonymised analysis of the quantitative data similar to Everard, M., et al., (2012).

4.3 Stoneyford ICW Data Collection

A manual sample (commonly known as a grab sample) from the inlet and outlet of each of the 5 full-scale ICW treatment ponds was taken on a weekly basis by NIW in accordance with their sampling guidelines. Weekly intervals were chosen as this is a common sampling procedure for similar studies on ICWs (Dong, Y., et al., (2011; 2012); Kayranli, M., et al., (2009)). The samples were transported to the NIW laboratory in Altnagelvin. They were tested for BOD, COD, Total Suspended Solids and Ammonium using standard NIW operating procedures which were not available at time of writing.

The NIW laboratory procedures are UKAS Accredited and ISO17025 Certified. Analysis of the grab samples was made available by NIW for a 19 month period from January 2016 to July 2017. The Stoneyford ICW weather station continuously monitored air temperature, precipitation, wind speed, wind direction and humidity. This was supplemented with weather data recorded at the nearby Aldergrove Airport from the MetOffice archives.

4.4 Small Scale Test Rig Data Collection

Manual flow rates were taken at the inlet and outlet of each of the 8 test beds at weekly intervals from August 2016 to April 2017. Figure 4.6 shows flow rate being measured using a 2 litre measuring container. Wastewater level was recorded using the gauge fixed to the inside of each the test bed as seen in Figure 4.7.



Figure 4.6 Manual flow samples taken at outlet of ponds.

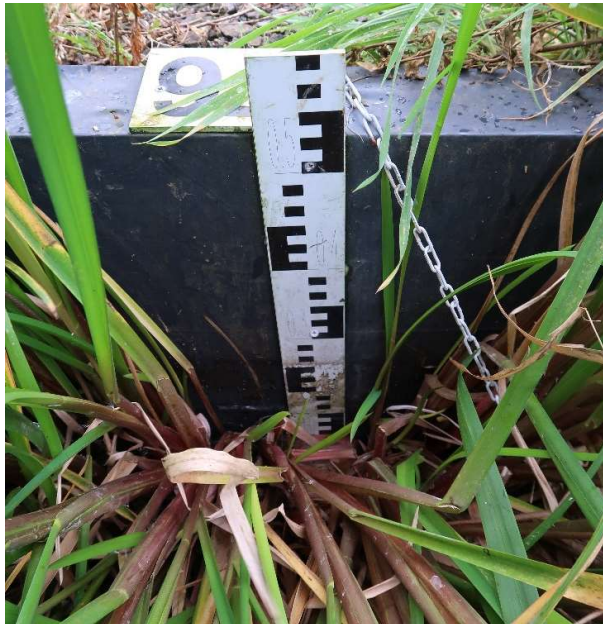


Figure 4.7 Depth gauge fixed to inside of Test Bed 6.

A manual grab sample from the outlet of each of the 8 test beds was taken on a weekly basis by NIW in accordance with their sampling guidelines. The samples were transported to the NIW laboratory in Altnagelvin. They were tested for BOD, COD, Total Suspended Solids, Total Nitrogen, Total Phosphorus, Ammonium, pH and E-Coli, using standard NIW operating procedures. The NIW laboratory procedures were UKAS Accredited and ISO17025 Certified. Sampling data was made available by NIW for a 9 month period from August 2016 to July 2017. Plant growth in each of the test beds was monitored visually.

4.5 Methods Used for the Drone Study

A drone was used for vegetation based investigations of the 5 ICW ponds during 4 site visits in December 2016, and February, April and July 2017. The drone used was a DJI Phantom 4 (Figure 4.8). This provided photographic and 4k video images for analysis. The DJI Phantom 4 could record video in Intelligent Flight Mode which allowed it to fly along a prearranged flight path using waypoints. During 4K video recording the drone was flown at an altitude of 10 – 15m with the camera facing directly towards the ground.



Figure 4.8 DJI Phantom 4 Drone (Martin, J., 2016).

The still images collected for vegetation analysis were taken from an altitude of 120m which allowed for the whole pond to be captured in a single image. A video survey of a single pond took approximately 10-15 minutes. Individual images of each pond took approximately 5 minutes.

Image Pro 9.3.1 was used to analyse single images of each pond. 3DF Zephyr Aerial Educational Version 3.301 was used to analyse the 4K video to reconstruct 3D models of each pond. Full step by step guides were developed for each method (Appendices B and C).

The following is a summary of the single image analysis method used to evaluate pond vegetation growth. Google Earth Pro was used to scale each pond (Figure 4.9). A pond image was opened in Image Pro 9.3.1 and calibrated using this Google Earth Pro data (Figure 4.10). The pond area from the edge of the water surface was selected as the region of interest (ROI) as shown in Figure 4.11. Using the Threshold tool, individual areas of interest (AOI) representing surface water, green vegetation and brown vegetation were selected and their areas determined (Figures 4.12 – 4.14).

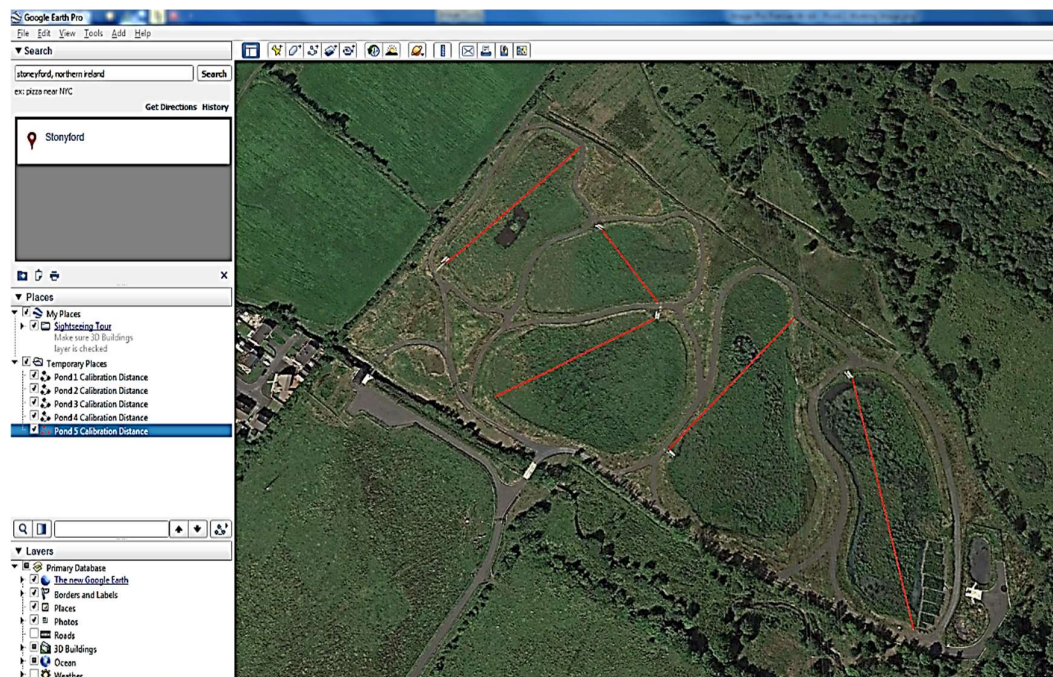


Figure 4.9 Pond Calibration Distances using Google Earth Pro.

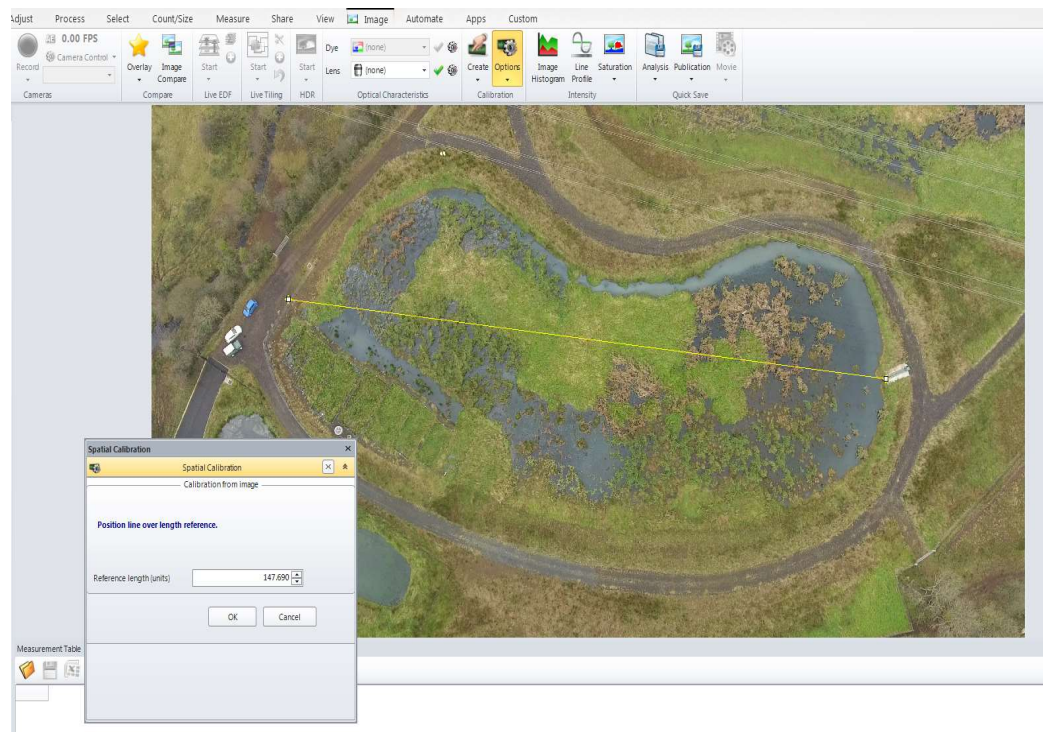


Figure 4.10 Pond 1 December 2016 calibration. Control distance highlighted.

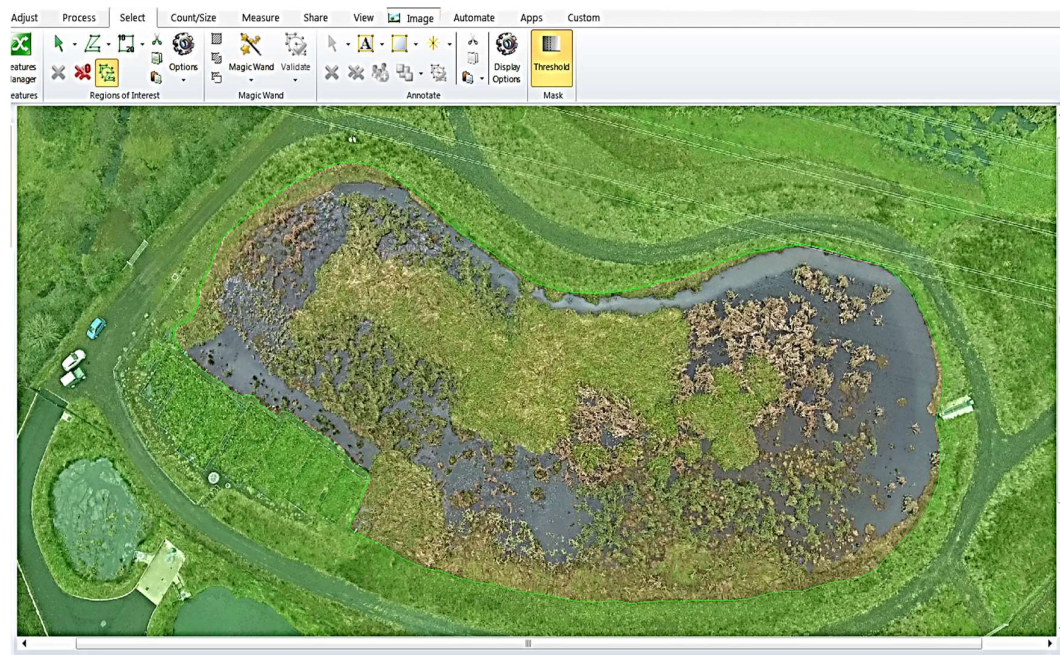


Figure 4.11 Pond 1 December 2016 Region of Interest (ROI) highlighted.

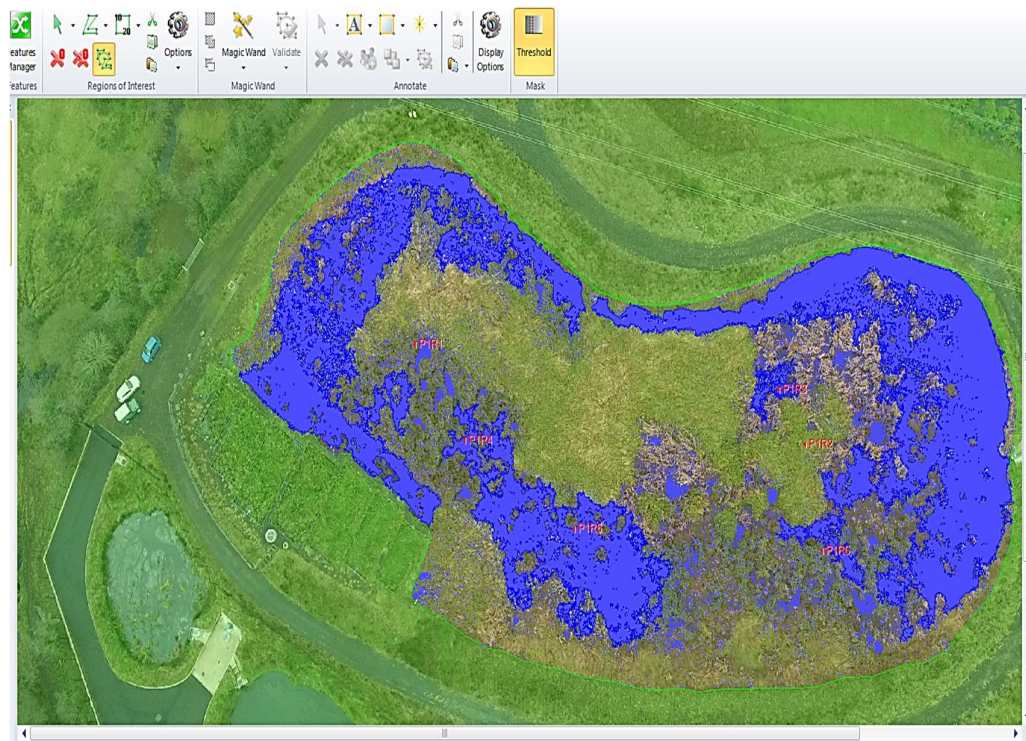


Figure 4.12 Pond 1 December 2016 surface water area threshold selection.

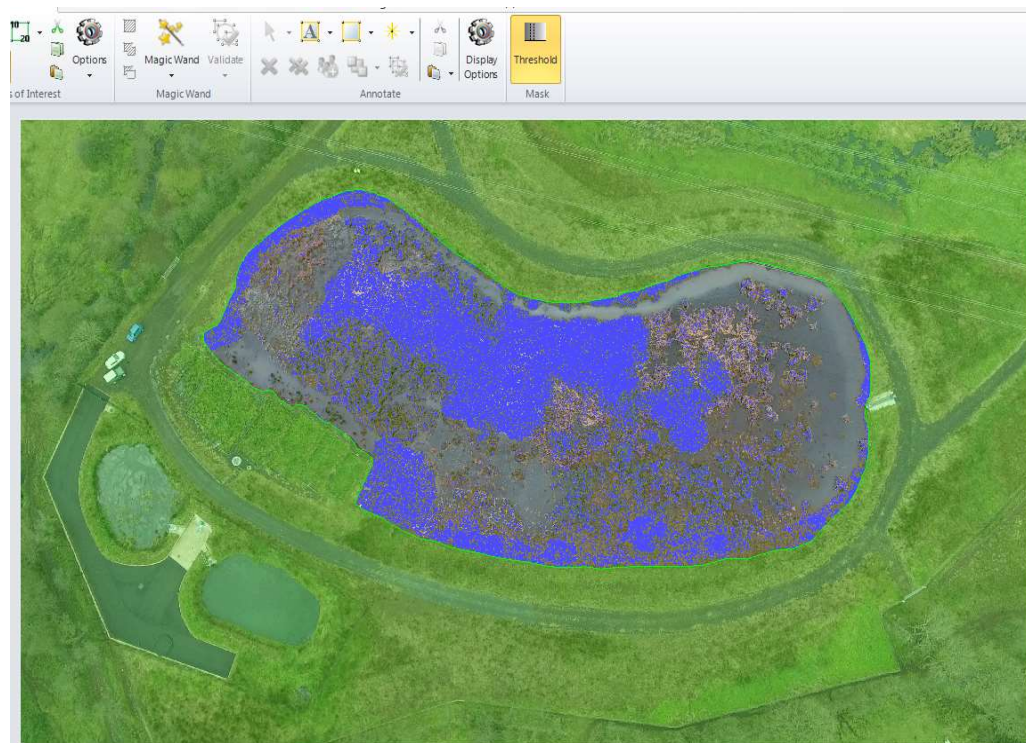


Figure 4.13 Pond 1 December 2016 green vegetation area threshold selection.

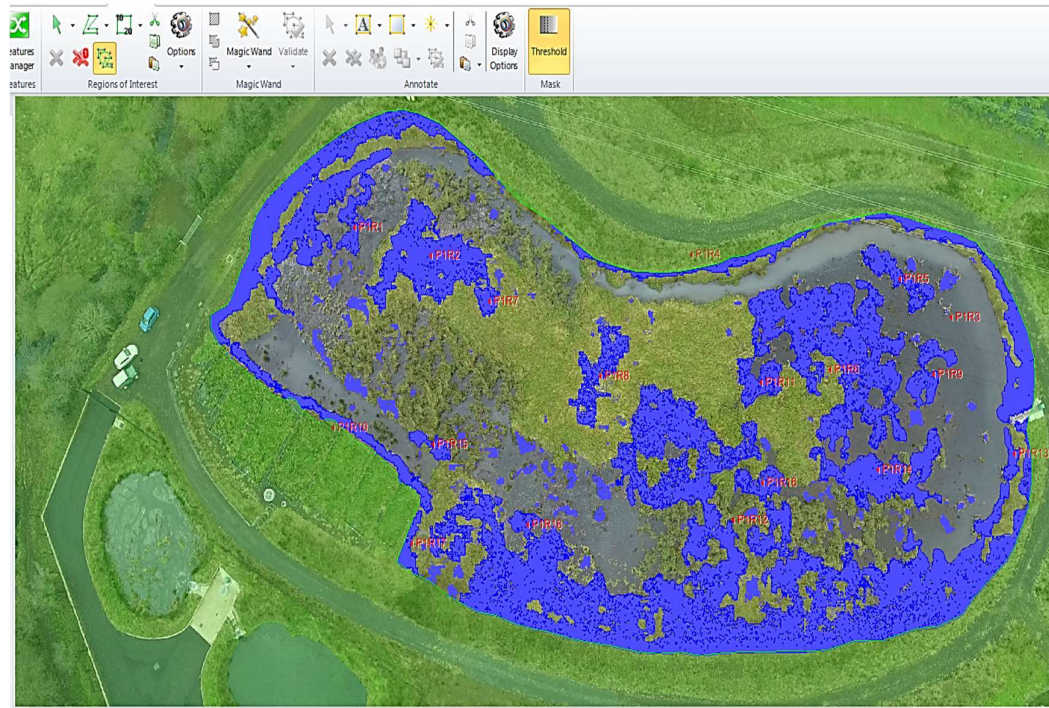


Figure 4.14 Pond 1 December 2016 brown vegetation area threshold selection.

The following is a summary of the 4K video image analysis method developed to create 3D models of each pond to evaluate vegetation growth using 3DF Zephyr Aerial software. The 3D modelling process involves 5 stages i.e. image extraction, sparse point cloud generation, dense point cloud generation, mesh extraction and textured mesh generation.

The software first extracts single images (Figure 4.15) from the 4K video. These are used to generate a 3D model using the steps detailed in Appendix C. Default software settings were used. The 3D model was scaled using waypoint information obtained from a site survey using a total station (Figure 4.16).

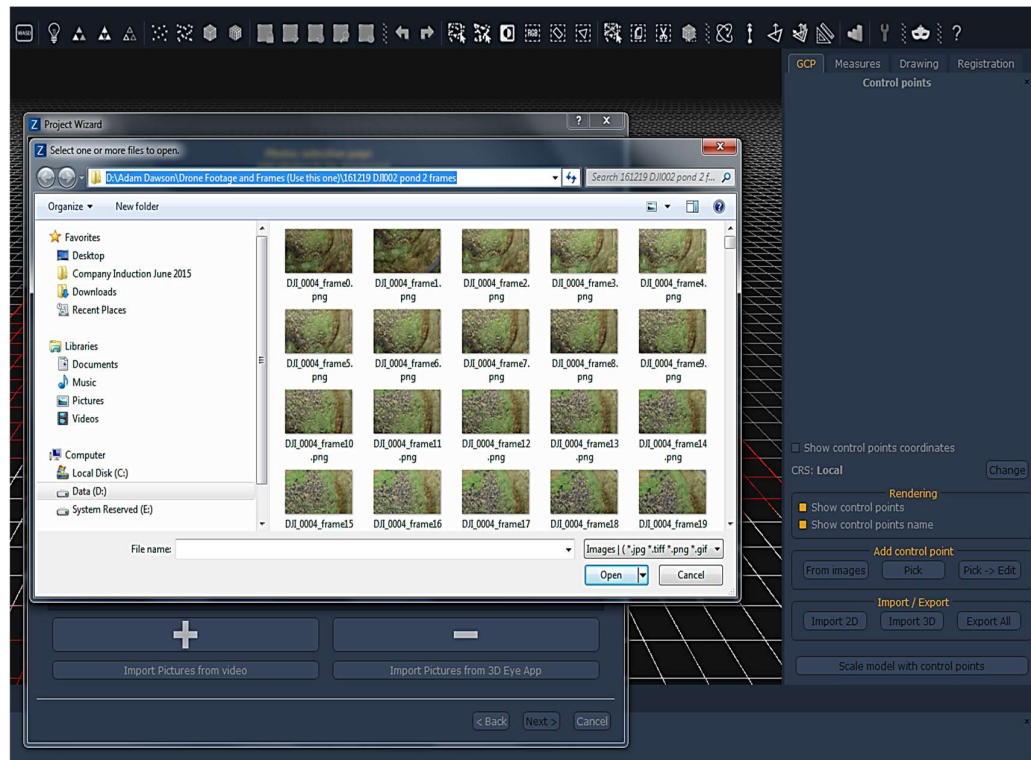


Figure 4.15 Extraction of single images from 4K video file.



Figure 4.16 Topcon Total Station and Tripod located at the outlet of Pond 1.

Figures 4.17 – 4.21 show example 3D models for each of the 5 ponds. The blue triangles are the single images extracted from the 4K video and show the drone flightpath. The red dots in the 3D model are the waypoint control points. The green lines show the measured distance in metres between control points measured using the total station capable of sub-centimetre accuracy.

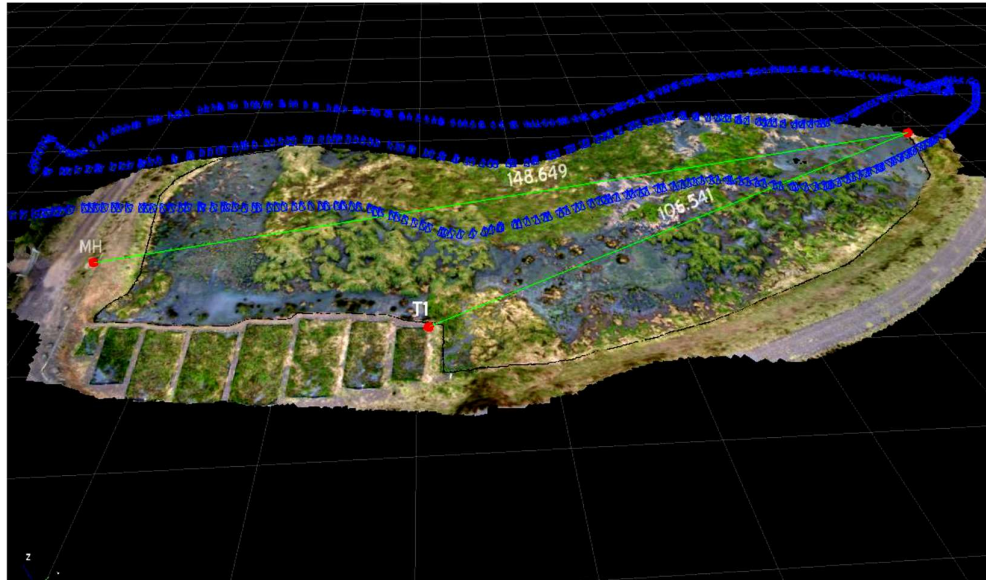


Figure 4.17 3D model for Pond 1 and Test Rig.

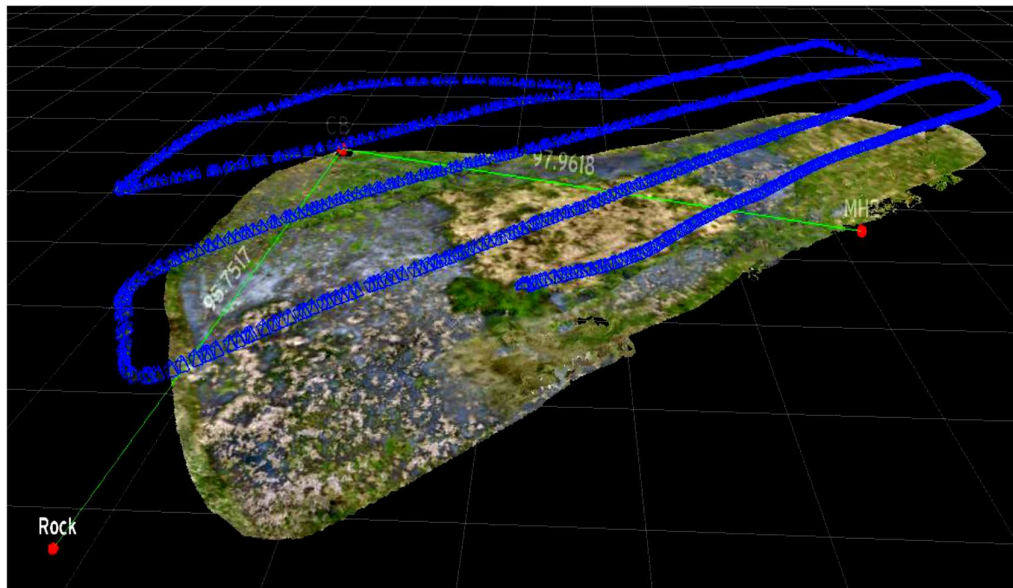


Figure 4.18 3D model for Pond 2.

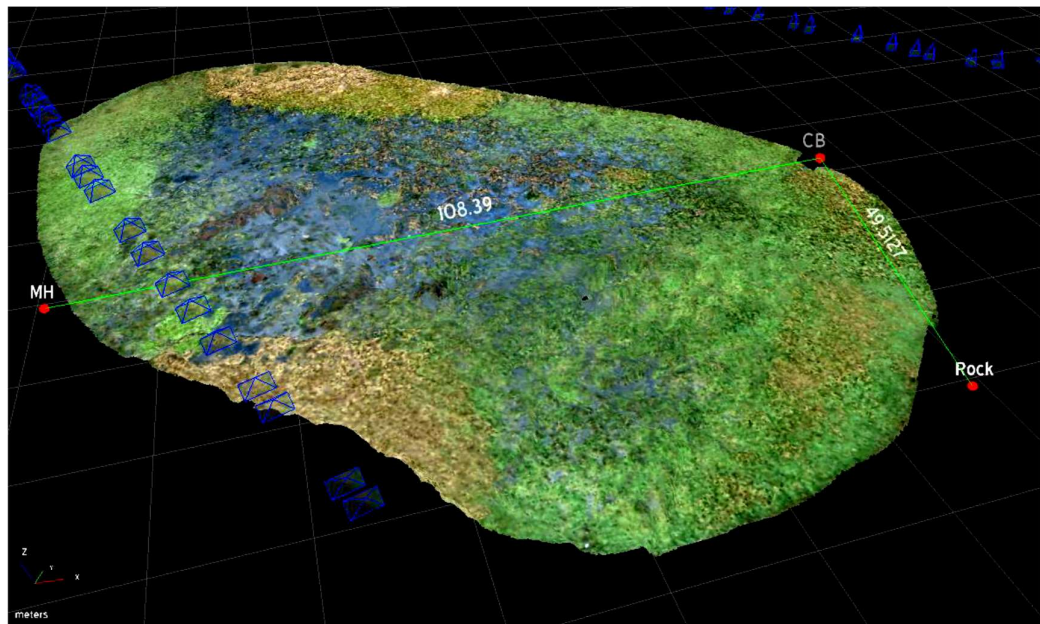


Figure 4.19 3D model for Pond 3.

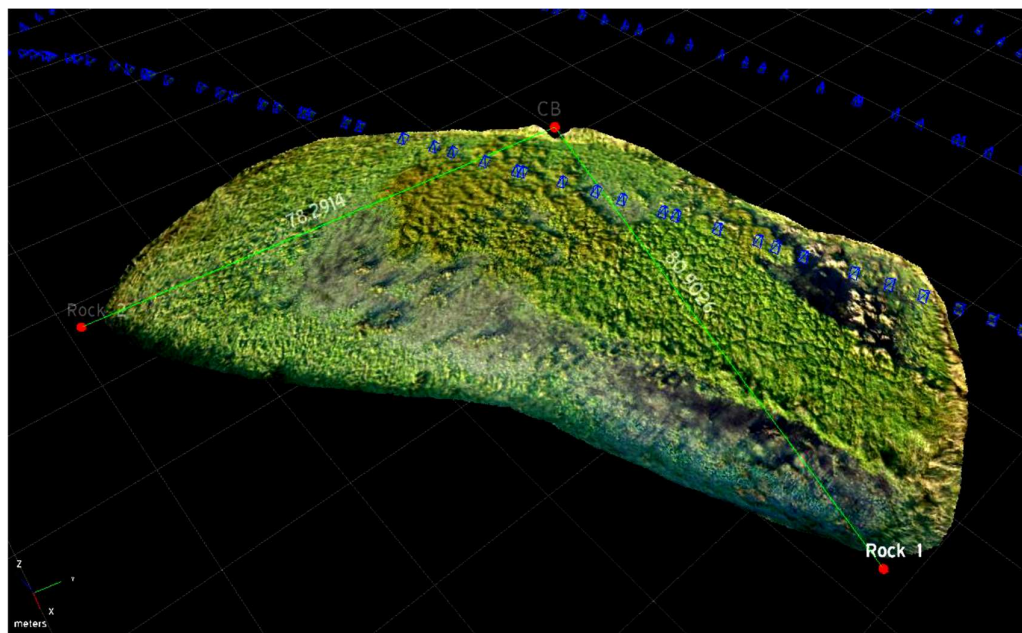


Figure 4.20 3D model for Pond 4.

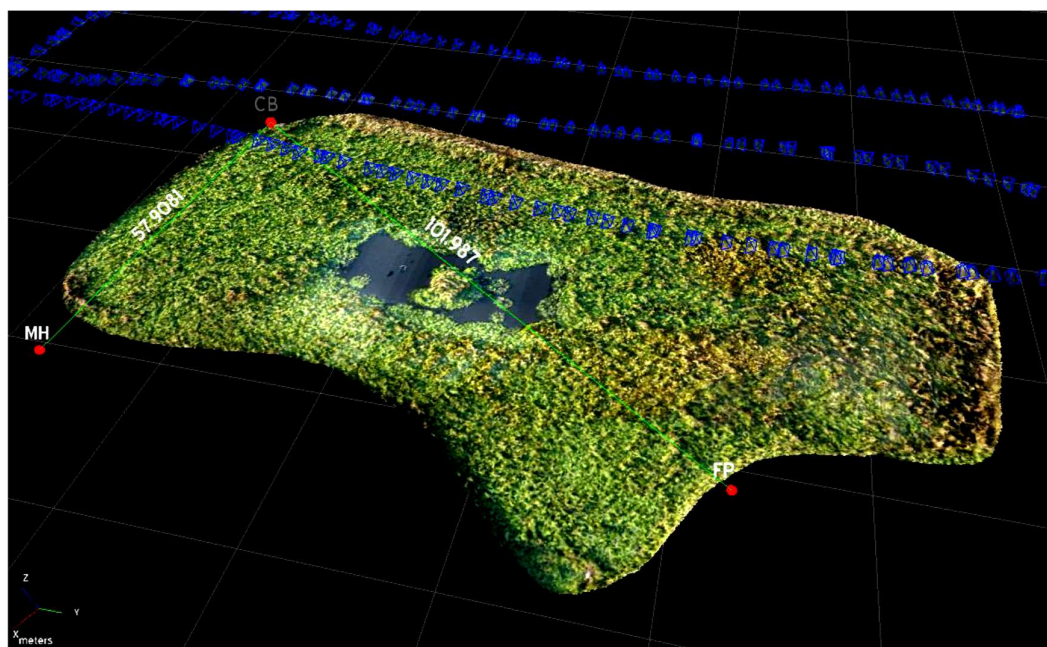


Figure 4.21 3D model for Pond 5.

CHAPTER 5. RESULTS

5.1 Introduction

This chapter will describe and analyse the results of the studies described in Chapter 3. The outcomes of the stakeholder engagement will be discussed. The findings from the full scale ICW and Test Rig will be detailed and analysed on the performance indicators of water quality. The data obtained from the drone study will be reviewed and analysed with regards to their application to monitoring plant performance of an ICW.

5.2 Results and Discussion of Stakeholder Engagement

This section will describe and analyse the overall responses given by the stakeholders for each of the discussion points relating to the 7 objectives listed in Table 4.1. Few of the stakeholders wrote their thoughts into each of the sections within the Feedback Booklet. The audio recording allowed further detail to be documented based on the discussions.

Please detail your current knowledge of ICWs, including their relevance to and context within Policy Frameworks and Sustainable Development Objectives:

This discussion point relates to Objectives 1-3 as listed in Table 4.1. At the beginning of the session stakeholders were asked to introduce themselves and give a brief account of their background and any previous knowledge they had of ICWs. From this it was clear that the stakeholders had limited previous knowledge of either the concept of or the processes involved in integrated constructed wetlands. They were keen to gain a better understanding. After the PowerPoint presentation stakeholders asked questions with regard to this research project with NIW including the type of wastewater being treated, methods of measurement and monitoring, and existing or similar projects in the UK and Ireland.

These questions were all related to the processes involved and developments of the research project itself. This indicated that the stakeholders had obtained enough knowledge and understanding during the PowerPoint presentation of the concept and processes involved in the development of constructed wetlands for wastewater treatment. They were now in a

position to provide relevant comments to discuss variables that impact on performance and appropriate appraisal methods.

Discussions considered the risks involved in developing an open system for the treatment of sewage. Stakeholders were concerned with Health and Safety regulations and the risks involved with allowing public access to a sewage treatment works. Issues included the exposure to pathogens, as well as the environmental risks that may be incurred should the system leak or overflow into nearby water courses and habitats.

With regards to the Water Framework Directive (2000/60/EC), stakeholders did not make any comment of their current knowledge. The topic of sustainable development provided a wider discussion with subjects stemming from each of the three pillars of sustainable development i.e. social, environmental, and economic (Brundtland Report, 1987).

Issues surrounding planning regulations and development constraints associated with sustainable development generated considerable discussion particularly with regards to land use and treatment capacities. Others raised issues on how the development of ICWs would impact on the local social and environmental communities again referring to health and safety concerns on both human populations and wildlife habitats. How the ICW would cope with extreme weather events such as flooding was discussed. This highlighted the need for rigorous assurance from NIW that there will be no significantly adverse implications incurred by society or the environment as a consequence of ICW implementation.

These discussions demonstrate that there is a lack of understanding on the overall performance of ICWs for wastewater treatment and that their success is determined by much more than their ability to clean wastewater. Thus, in order to fully evaluate the performance of ICWs, it is important to first identify the contexts in which their performance can be appraised and weight them appropriately.

Based on your previous knowledge and today's presentation can you identify the key variables which impact overall ICW performance?

This discussion point relates to Objective 4a as listed in Table 4.1. Stakeholders were asked to identify variables that would have an impact on ICW treatment performance. The variables

identified by the stakeholders were grouped according to the findings from the literature review as illustrated in Table 5.1.

Table 5.1 Identified variables and grouping.

Variables identified by Stakeholders	Variable Group from Literature
Area; Soil Capacity/Volume; Water Depth; Wetland Geometry.	Design
Influent Quality; Hydraulic Flow; Water Balance (evaporation/filtration).	Hydraulics
Seasonal Variations; Extreme Events; Evaporation; Precipitation; Transpiration	Climate and Climate Change
Plant species; Plant Performance; Plant Growth; Plant Life/Sustainability	Vegetation
Site Selection; Site Topography; Local Hydrology	Planning
Maintenance	Operation and Maintenance

The variables that impact performance identified by stakeholders can be categorised into four main categories recognised by literature; Design, Hydraulics, Climate, and Vegetation. Interestingly, the stakeholders identified a number of additional variables which could impact the performance of ICWs as seen in Variable Groups ‘Planning’ and ‘Operation and Maintenance’. This evidence confirms that the key variables that impact ICW performance had been identified within the literature. Evidence also illustrates that there are other variables which had not been identified, highlighting the limitations of available research in relating ICW performance to key stakeholder requirements. In order to achieve the main aim of the research project to provide knowledge and understanding to stakeholders, it must meet the needs and desires of those stakeholders, and not just address gaps in academic research. This discussion point within the stakeholder engagement session highlighted the importance of gaining stakeholder views.

Can you now weight the agreed variables in order of significance to influencing performance using the pyramid below?

This discussion point relates to Objective 4b as listed in Table 4.1. The stakeholders were asked to weight the variables in order of significance using the Pyramid of Significance Template shown in Figure 4.1. Results from the discussion indicate that the most significant variable would be the sewage quality being treated. The quality and volume of the sewage is the problem which needs to be solved, therefore the performance of all other variables is relative to the level of performance required, or capacity of the variables to treat the particular influent.

The second most prominent variable that stakeholders deemed to be significant in impacting performance were those held within the Planning variable group. This can be justified by understanding that planning limits what can be designed and built. If there were no planning constraints clients would be able to build an ICW at whatever size and design they required to treat wastewaters. However an ICW must be constructed within particular planning margins, thus limiting the design capacity of the wetland and impacting on subsequent performance. Another way in which planning impacts on the performance of wetlands treating wastewater is that the design must be sustainable for future use. Issues such as population growth and climate change will need to be considered in the original designs and planning procedures to ensure the system will be as effective as a wastewater treatment facility in the future as it is now, without the need for expanding or adding further treatment techniques.

The third variable group that was deemed to be of significance in ICW performance was that of Design, specifically in relation to surface area and wetland geometry. The design must be sustainable for future generations and have adequate surface area to be able to cope with the likely increase in loading caused by population growth. The design must also be accurate and appropriate to the application of domestic wastewater whilst still remaining considerate of social, economic and environmental implications. Thus, designing the constructed wetlands' size and shape will have significant impact on its wastewater treatment performance as it will influence the volume and application of treatment capacity.

The fourth significant variable was that of hydraulics. Stakeholders discussed how issues of hydraulic retention and hydraulic load were probably highly significant in impacting performance, but that external issues surrounding climatic and vegetative growth patterns

meant that control over hydraulic variables may be limited. Hydraulic retention time and loading are probably strongly influenced by the design of the wetland through surface area, water depth, geometry, soil composition, vegetation species and plant density. However, climatic changes can cause alterations in the water balance either directly through evaporation or precipitation, or indirectly through transpiration and plant uptake. Despite hydraulics being considered to influence ICW performance, issues with external conditions mean that even the most accurate hydraulic designs may be subject to unexpected performance in service.

The fifth variable was plants and soil. Again, it was discussed that these variables, despite having significant contribution to the treatment performance of constructed wetlands, are greatly influenced by external climatic conditions beyond human control. It was agreed that despite having appropriate types and volumes of vegetation and soil, changes in climate and weather can produce unexpected performance in service.

Operation and Maintenance was not deemed to be of significant influence. Maintenance would either help maintain performance levels of other variables of design, hydraulics, and planning or have a slight to moderate adverse impact if not maintained. It would not directly influence the overall wastewater treatment performance.

The variable group which was deemed to be of least significance was that of climate and climate change. Despite being considered as having a substantial impact on other variables the climate may not directly influence the ability of ICWs to treat wastewater. It was also noted that climatic conditions are not controllable or manageable variables and should therefore be considered only as an impact on the performance of other variables, and not as a direct variable itself.

Once discussions had finished and stakeholders were satisfied that they had appropriately weighted the identified variables, they were shown the Pyramid of Significance based on literature as shown in Figure 4.2.

The Pyramid of Significance illustrates that the most significant variable identified by literature is that of sewage quality (influent quality), followed by plant (vegetation), soil and surface area. Hydraulic variables and other issues of design were secondary, with climate and effluent quality (required standards) being those which are deemed to be considered least significant. From the results of the discussions at the stakeholder session, a similar pyramid based on their views and knowledge was drawn up as seen in Figure 5.1.

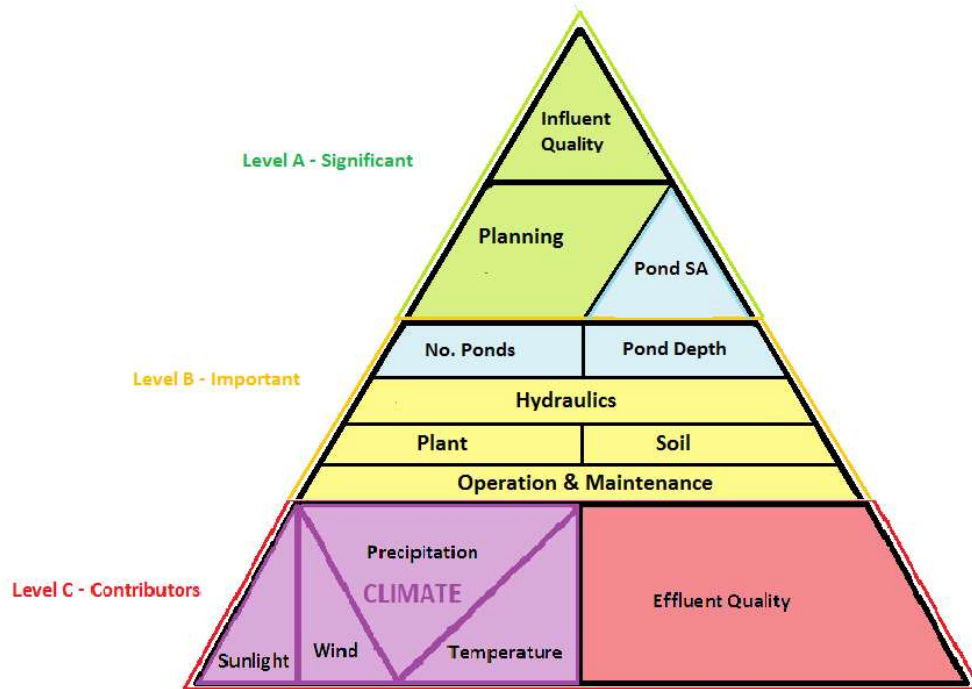


Figure 5.1 Pyramid of Significance Key Variables based on Stakeholder Engagement.

The Stakeholder Engagement Pyramid of Significance is similar to the Pyramid of Significance derived from the literature review (Figure 4.2). Influent Quality was the top priority and Pond Surface Area being classed as significant; Hydraulics, Pond Depth and Pond Number classed as important; and Climate and Effluent being classed as contributors.

Figure 5.1 has the addition of Planning within the significant section. Plant and Soil has been reduced to the Important level. Operation and Maintenance has been added to the important level.

The stakeholder engagement session agreed in general with information gathered from the literature review. However, it is now apparent that literature may have failed to adequately consider design, operation and maintenance of an ICW. For example, the theoretical 90 day retention time or the surface area per person equivalent. The impact of wastewater load as it flows through the ICW ponds. The migration of weeds or dominance of planted species within the ponds.

Based on your previous knowledge and today's presentation can you identify the key performance criteria for overall ICW appraisal?

This discussion point relates to Objective 5a as shown in Table 4.1. This formed the second stage of the stakeholder engagement and discussed the various ways in which ICW performance could be appraised in addition to wastewater treatment. The stakeholders identified a number of appraisal contexts which are grouped to allow for literature comparison and shown in Table 5.2.

The appraisal contexts identified by the stakeholders can be grouped into the 6 main contexts identified by literature. The stakeholder engagement identified additional appraisal contexts related to Pollutant Removal; Land Use, Economics, Operation and Maintenance, Ecology, Social Impact, Carbon Footprint, and Climate Change Mitigation. Stakeholders identified 4 additional groups which had not been considered by literature; Planning, Health and Safety, Political Consideration, and Social Perception.

Literature had partially considered how an ICW had impacted the local community. However, it had not fully considered how the community views an ICW as a method of treating domestic wastewater. The stakeholder engagement highlighted numerous ways in which ICW performance could be evaluated and highlighted that literature has not fully considered all of the contexts that are considered important to these key stakeholders.

Table 5.2 Identified Appraisal Contexts and Groupings.

Appraisal Context from Stakeholders	Appraisal Group Related to Previous Literature
Application Alteration, Environmental Assessment, Sustainability, Risk Assessment / disaster mitigation, Landscape Impact, Design	Planning
Wetland Size; Existing Land Use; Land Sustainability; Land Availability.	Land Use
Land Cost; Construction Cost; Energy Consumption; Economic Sustainability; Cost Benefit Analysis; Whole Life Cost.	Economics
Operation Costs; Maintenance Costs.	Operation and Maintenance
Risk of Pathogens; Public Access; Vermin; Odour; Flood Risk.	Health and Safety
Treatment Requirements; Water Framework Directive; Sustainable Development Strategy; Carbon Reduction	Political Considerations
Invasive Species Risk; Contamination to Food Chain; Wildlife Habitat;	Ecology
Land Use; Vermin; Health and Safety.	Social Perception
Carbon Reduction; Greenhouse Gas Emissions; Energy Consumption	Carbon Footprint
Flood Prevention; Disaster Mitigation; Climate Sensitivity	Climate Change Mitigation

Can you now weight the agreed criteria in order of significance to overall ICW performance appraisal?

This discussion point relates to Objective 5b as shown in Table 4.1. The stakeholders were asked to weight the contexts in order of significance. Pollutant removal was unanimously considered the most significant as this is the main purpose of the ICW. Similar to the Variables weighting, planning and land use were next. This was justified in a similar way to the variables. If land use and planning constraints were not an issue the ICW could be designed to optimise treatment of the wastewater.

The second most significant contexts were those of economics and carbon footprint. Stakeholders stated that their main considerations within any development evaluation is to understand if the development is fit for purpose and is economically achievable. Therefore, the ICW design must consider economic cost in terms of construction, energy consumption (carbon footprint) and operation and maintenance requirements.

The third most significant contexts were Social Perception and Political Considerations. The development of an ICW must meet the requirements and objectives set out by key policy frameworks and sustainable development strategies. Local community issues such as odour, health and safety of pets and children using the community area and vermin risk need consideration.

The stakeholders gave the lowest weighting category of appraisal contexts to Ecology and Climate Change Mitigation. The stakeholders agreed that issues surrounding ecological impacts and climate change were very important topics to be considered in the appraisal of ICWs in the treatment of wastewater, especially given the natural context in which the systems are designed. However, they felt that issues associated with economic stability, sustainable planning and development, carbon and energy reductions, were more important than concerns over adverse ecological impacts and climate change mitigation.

After the discussions stakeholders were shown a Pyramid of Significance based on literature findings and research as seen in Figure 4.3. The stakeholders were surprised to see that economics and land use were ranked beneath operation and maintenance issues. They were also surprised by the low ranking of carbon footprint within literature considering its importance within the built environment. Figure 5.2 shows the Pyramid of Significance based on the stakeholders views from the discussions.

Although Figure 4.3 and 5.2 are not similar, they have common themes with pollutant removal being of significant consideration and climate change being weighted amongst the lowest. What was of particular interest was the increase in significance of economics and carbon footprint in Figure 5.2. Planning, social perception and policy considerations are also more significant. This highlights that the literature reviewed was not fully representative of the key issues facing stakeholders in the implementation of ICWs for real life applications.

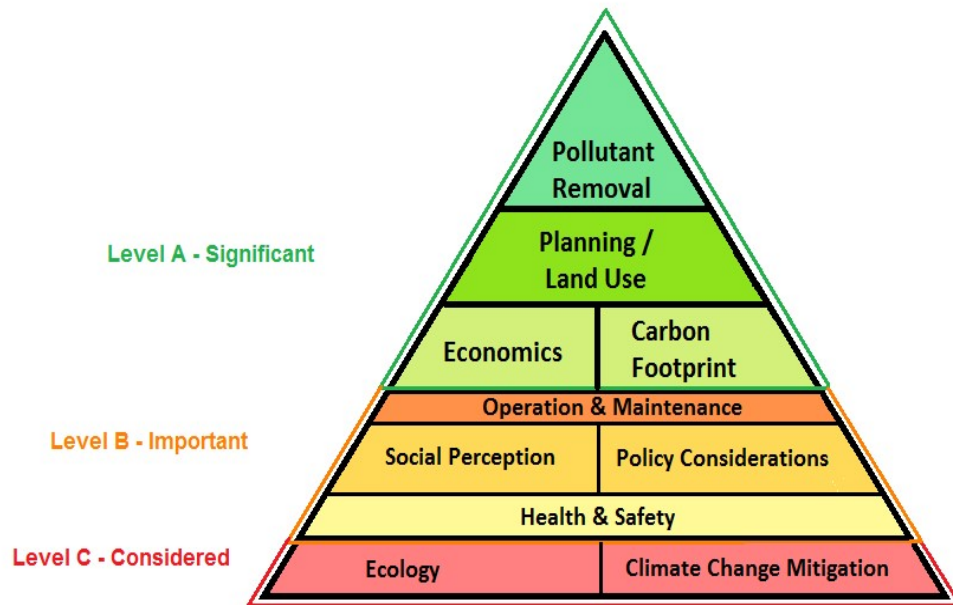


Figure 5.2 Pyramid of Significance Appraisal Context based on Stakeholder Engagement.

What is your opinion on the future of ICWs in terms of implementation and additional/alternative applications?

This discussion point relates to Objective 6 as shown in Table 4.1. This section of the stakeholder engagement session aimed to obtain the views of stakeholders on the future of ICWs with respect to more efficient, effective and sustainable designs. The general outlook for future implementation of ICWs was very positive with all stakeholders agreeing that there was a place for them in the sustainable development of wastewater infrastructure.

What are your opinions on an ICW Best Practice Design Guide to develop a document applicable to various industries and applications; what key elements should be included within the document?

This discussion point relates to Objective 7 as shown in Table 4.1. The purpose of the stakeholder engagement was to discuss the use of an ICW for treating domestic wastewater in Northern Ireland. This last part of the stakeholder discussion considered how an ICW Best Practice Design Guide could be adapted for other types of water treatment in Northern Ireland.

Each stakeholder had a different view as to what should be included within a design guide. The design guide must be relevant to the different applications and industries. Regulators will need different types of information. There may need to be a design guide matrix to help decide the appropriate design for specific influents.

5.2.1 Summary of Stakeholder Engagement

The aim of this stakeholder engagement session was to gain the attitudes and opinions of key stakeholders on the key variables and appraisal contexts that influence the performance of an ICW in the treatment of wastewater. The stakeholder engagement session proved to be very valuable as it highlighted the following points:

- The stakeholders identified limitations with available literature,
- Stakeholders should be involved at an early stage in the design process,
- Stakeholders are not necessarily aware of all the literature available,
- Health and safety of the local community must be considered if the holistic objectives of an ICW are to be achieved.

5.3 Stoneyford Full-Scale ICW Results

This chapter considers the data obtained from the Stoneyford full-scale ICW ponds. It is based on the water samples taken from the outlets of each pond on a weekly basis over the sampling period of 19 months (January 2016 – July 2017). Samples were analysed on the four main wastewater treatment contaminants considered important in Northern Ireland Water i.e. BOD, Suspended Solids, Ammonia (NH₃-N) and COD. Data tables for each of the contaminants are given in Appendix D. This chapter considers seasonal and weather effects on the ICW treatment performance. The treatment performance is related to changes in vegetation cover and surface water. Issues that arose within Pond 1 during the testing period are discussed to highlight potential problems for future ICW developments.

5.3.1 Comparison of ICW Inlet and Outlet Analysis

This section shows how the 5 ponds of the ICW treat wastewater by comparing inlet (leaving Sludge Pond) and outlet data (leaving Pond 5). Figure 5.3 compares the Inlet contaminant levels over the sample period. Figure 5.4 compares the Outlet contaminant levels over the sample period. Figure 5.3 shows that Inlet levels of all contaminants rapidly vary over a wide range and are all above their Water Order Consent (WOC) levels. COD does not have a WOC.

Figure 5.4 illustrates that outlet levels of all contaminants are much lower than Inlet levels with a narrower range of fluctuation. BOD levels are consistently below WOC of 15mg/l with only 1 sample of 40mg/l in November. Suspended Solids are also typically below WOC of 25mg/l. High levels of suspended solids above 30mg/l were recorded in June, August and December 2016 and July 2017. Outlet levels of COD are more stable than Inlet levels across the sample period. Ammonia levels are below the WOC of 3mg/l for the majority of the sampling period. However, consent was not met between the months of August 2016 and March 2017, and again in July 2017.

Overall, evidence illustrates that Stoneyford ICW can successfully treat wastewater for BOD, Suspended Solids, and COD during the first 19 months of its life. More research is needed to improve the early life performance of a new ICW in treating Ammonia.

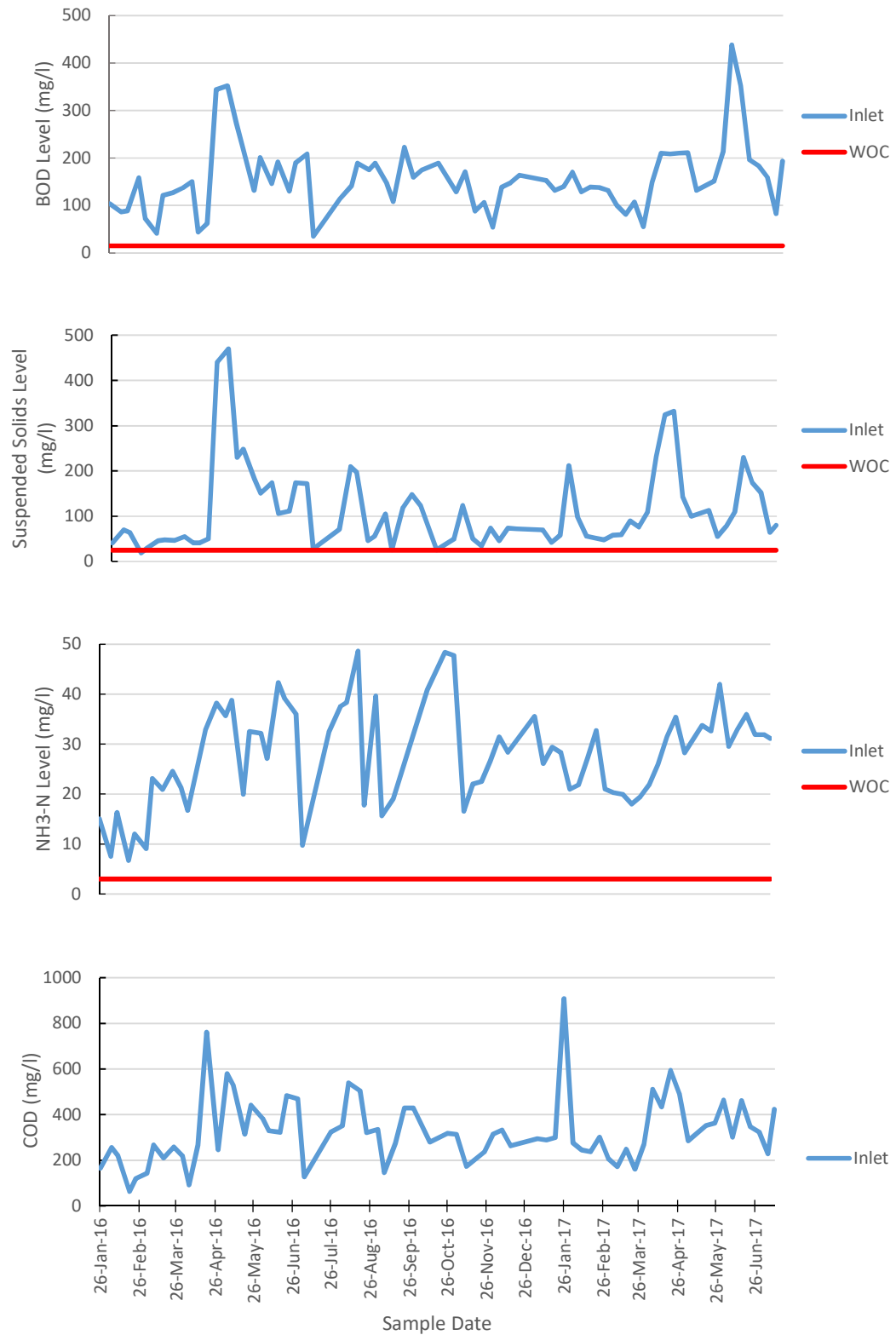


Figure 5.3 Comparison of ICW inlet water quality indicators over time.

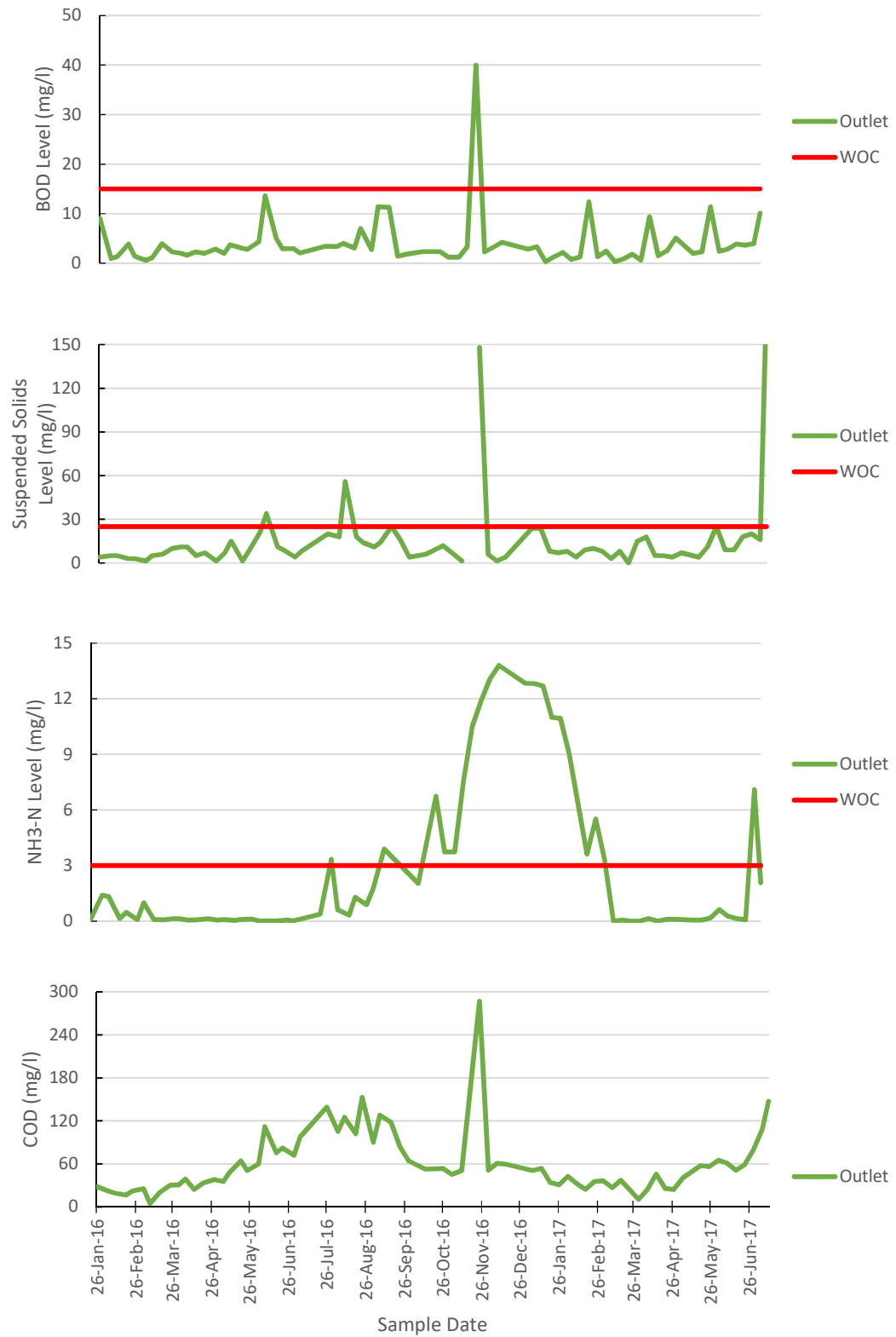


Figure 5.4 Comparison of ICW outlet water quality indicators over time.

5.3.2 Water Quality between Ponds/Area Analysis

This section illustrates the results in relation to the water quality performance of the ICW across the area of each of the 5 ponds to determine differences between the performances of each pond. The results for BOD removal is shown in Figure 7.5.

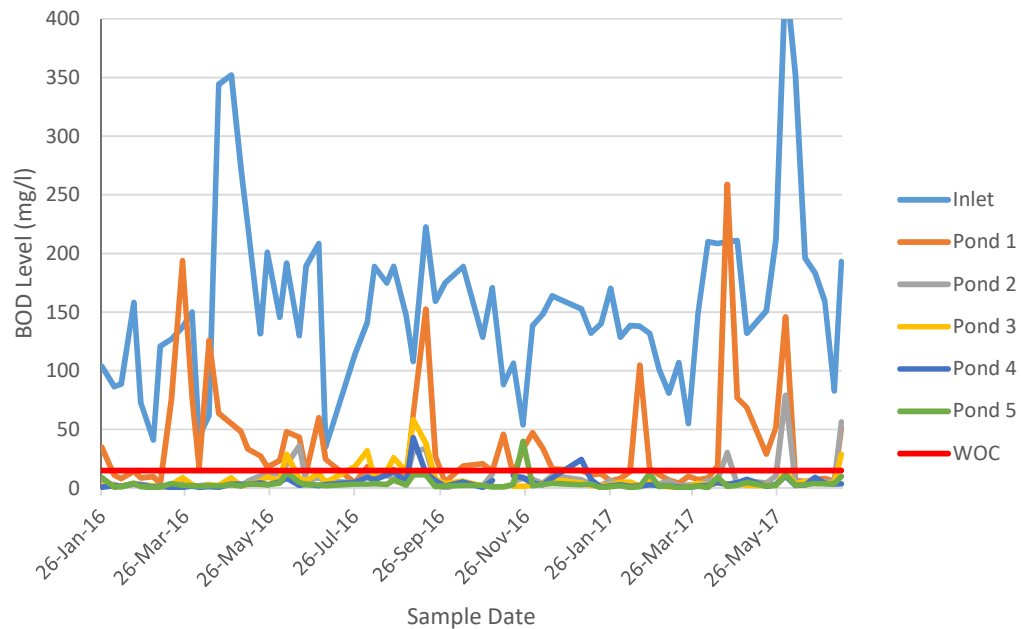


Figure 5.5 BOD Levels per Pond over Time.

Figure 5.5 illustrates the change in BOD levels per pond across the testing period of 19 months plotted as a line graph. This demonstrates that this method is not an appropriate way to illustrate how each of the ponds perform over time as it does not account for the retention time within the ponds. For example, the BOD of 152mg/l noted in Pond 1 in September cannot be related to poor performance of Pond 1 if the Inlet levels at the same date are 223mg/l. Rather, the September level in Pond 1 may be related to the high inlet rates of 352mg/l noted in April. In order to demonstrate the effects of retention time and performance of each pond, the treatment performance of ammonia will be discussed in more detail (Figure 5.6).

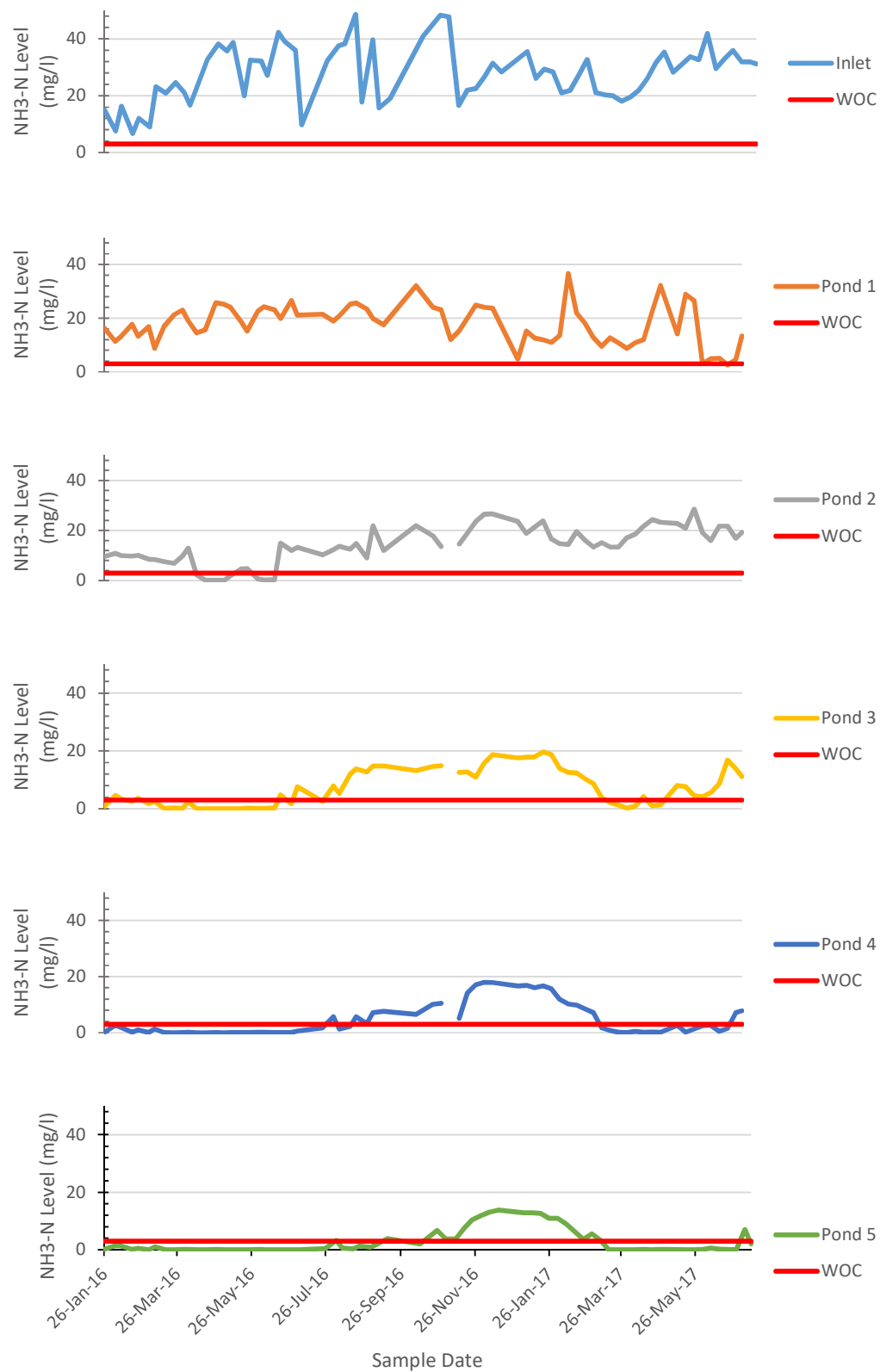


Figure 5.6 NH₃-N levels per pond over time.

Figure 5.6 illustrates the change in ammonia levels (measure as Ammoniacal nitrogen) per pond across the testing period of 19 months. Inlet levels fluctuate heavily throughout the year, particularly between the months of May to November reaching highs of over 47mg/l.

Pond 1 shows much more stable levels, although still follows a similar pattern of gradually increased levels until November. Pond 2 begins stable, before dropping rapidly to 0.06mg/l by May. However, levels rapidly increase to 14.94mg/l before the end of June and remain high for the rest of the study.

Ponds 3, 4 and 5 show similar trends with $\text{NH}_3\text{-N}$ levels remaining below the WOC for the first 6 months of testing. However, in June 2016 Pond 3 begins to steadily increase and Ponds 4 and 5 follow a similar pattern by the end of June/ beginning of July 2016. The 3 ponds continue to increase steadily until January 2017 when they begin to decrease below the WOC by the end of March 2017. Pond 3 then records another spike of 4.27mg/l at the beginning of April 2017 and continues to rise in a similar trend to the previous year with Ponds 4 and 5 continuing to follow by June 2017.

Ponds 3, 4 and 5 follow an 'n' shaped curve, seemingly beginning around spring each year. It could be suggested that their performance is cyclical or seasonal. It may be suggested that it could take a period of time longer than the 2 years of this study for the ponds to reach a state of equilibrium. It may also be suggested that the ICW is more susceptible to seasonal impacts in its early life. Another possible explanation for this could be related to an influx of wildlife or migratory birds. It is well known that many species of migratory birds flock to the wetlands of Northern Ireland during the autumn to spend the winter in milder climates; this fact coupled with the direct intent of the design of Stoneyford ICW to encourage wildlife into the area suggests that an influx of birds is plausible.

This would have an impact on the ammonia levels due to an increase in droppings at the later stages of the wetland, where the plants have less retention time to treat the wastewater before being discharged. It is apparent from Figure 5.6 that there is a period of retention between the ammonia levels reaching above WOC levels in Pond 3 in July, Pond 4 in August and Pond 5 in October. It is also apparent that the period of time taken to reduce ammonia levels back below WOC reduces over time. Pond 3 takes 9 months, Pond 4 takes 8 months and Pond 5 only 5 months. This evidence would suggest that having more than 5 ponds could reduce the levels of ammonia at the discharge point further and mitigate the effects of high fluctuations caused in earlier ponds.

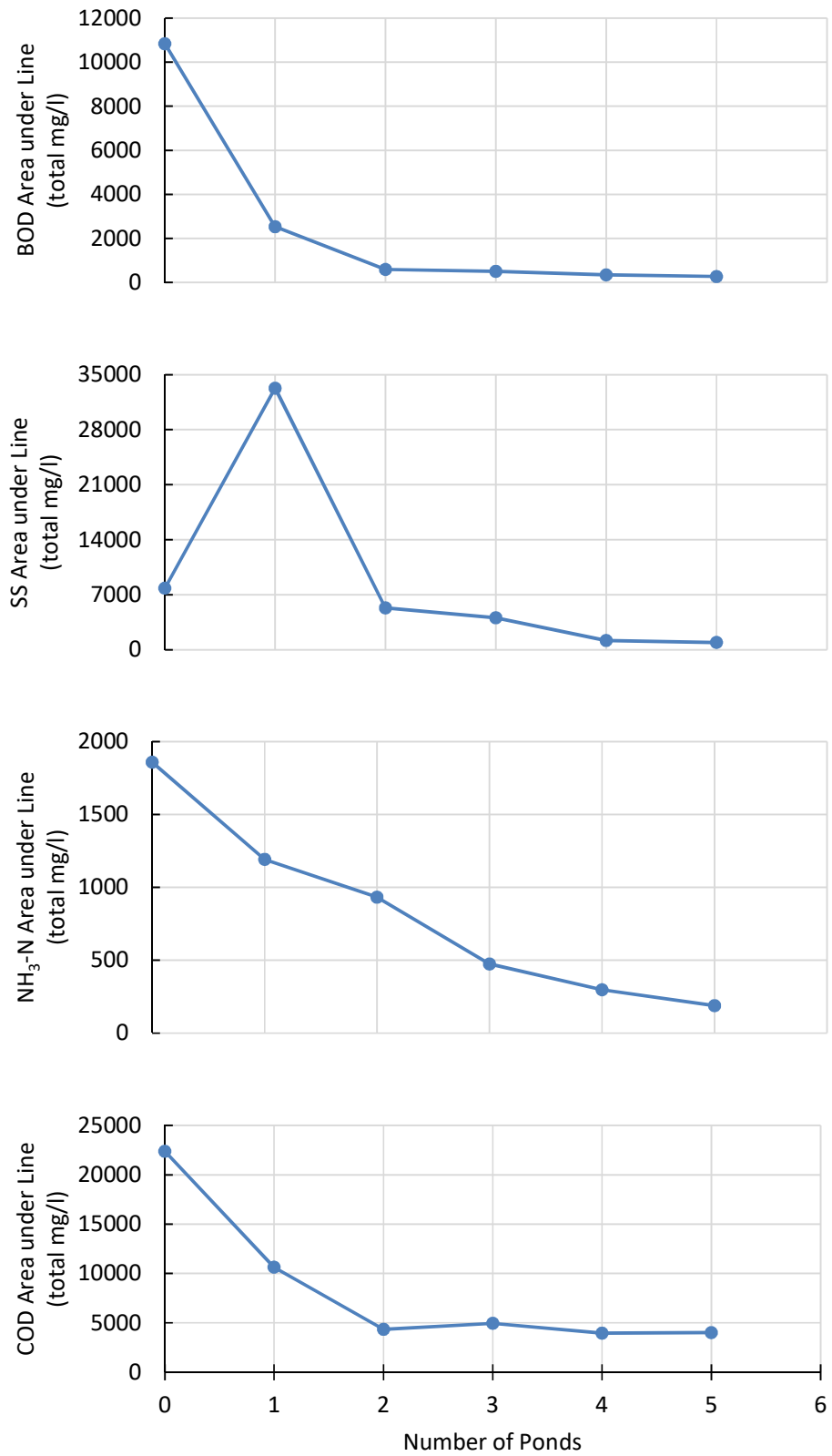


Figure 5.7 Area under line graphs for each contaminant plotted against number of ponds.

The results have indicated that there is evidence to suggest that each of the ponds performed differently in treating ammonia with Ponds 1 and 2 typically less stable than Ponds 3-5. Results also indicate that retention time and wastewater concentration within ponds must be considered to fully analyse the treatment performance of each individual pond.

The results of the total contaminant levels over the 19 month sampling period within each pond were plotted against the number of ponds. Using this data an area under the line graph was plotted for each of the contaminants as shown in Figure 5.7. This shows the total amount of contaminant within each of the ponds over the period of the 19 month study. This illustrates the correlation between the number of ponds and the amount of contaminant within the pond. From this it can be seen that the treatment of wastewater within the system improves with the number of ponds. BOD levels fall quickly and by Pond 2 seem to have reached equilibrium. There is a significant spike in the data leaving Pond 1 for SS during this early life sampling period. This may reflect the continuing issues with Pond 1 relating to water depth/ open water and engineering works associated with this particular pond. It may also be influenced by bird life taking advantage of the open water. There is a steady drop in ammonia through the 5 ponds. The data suggests it may not have reached equilibrium and a 6th pond may have been necessary. It is noted that the ICW has not reached maturity during the period of this investigation. COD follows a similar trend to BOD. Representing the data in this way illustrates the importance of the relationship between ICW performance and number of ponds and is of use in the initial design process.

Further research is recommended to determine how retention times within each of the ponds changes over time. This could potentially be used to predict future performances of the ponds and aid in the optimisation of future ICW design.

5.3.3 Water Quality against Seasonal Variations

This section illustrates the results in relation to the water quality performance of the ICW against seasonal variations of precipitation, air temperature, wind speed and humidity over the sample period of one year, to determine if external conditions have a direct influence on wetland performance.

The weather data was supplemented from the MetOffice archives for the nearby weather station at Aldergrove Airport. Hourly weather data was obtained for the yearly testing period and was then combined into daily and weekly averages for the week prior to each of the sample dates as seen in Appendix E. This gives the representative weather conditions for the week prior to sampling.

Table 5.3 illustrates the significance in correlation between contaminants levels leaving Pond 5 and weather. Linear regression failed to find any meaningful relationships between contaminant levels and weather for the week prior to sampling. The results plotted for $\text{NH}_3\text{-N}$ against humidity are given in Figure 5.8 as this showed the most significant correlation between weather and treatment.

Table 5.3 Significance of weather variables against discharge water quality.

Contaminant	Weather Variable	Equation	R ² Value
BOD	Total Precipitation	$y = -0.0492x + 5.346$	0.0198
	Air Temperature	$y = -0.0535x + 4.8292$	0.0015
	Wind speed	$y = -1.3294x + 9.7886$	0.0564
	Humidity	$y = 0.1023x - 4.2565$	0.0069
Suspended Solids	Total Precipitation	$y = -0.1551x + 17.176$	0.0141
	Air Temperature	$y = -0.0265x + 14.191$	2E-05
	Wind speed	$y = -6.943x + 42.433$	0.1108
	Humidity	$y = 0.0963x + 5.8788$	0.0004
Ammonia ($\text{NH}_3\text{-N}$)	Total Precipitation	$y = -0.0525x + 3.6051$	0.0514
	Air Temperature	$y = -0.2354x + 4.6588$	0.0653
	Wind speed	$y = -0.401x + 4.1296$	0.0117
	Humidity	$y = 0.4224x - 32.934$	0.2787
COD	Total Precipitation	$y = -0.3959x + 75.035$	0.0197
	Air Temperature	$y = 5.2603x + 16.365$	0.2123
	Wind speed	$y = -15.849x + 131.81$	0.1238
	Humidity	$y = -0.7092x + 126.11$	0.0049

Overall the results demonstrate that although slight trends can be seen for each of the contaminants against the various weather variables, the relationships show no statistical significance. Thus, it can be concluded that weather and seasonal variations have little to no impact on the ICW ability to treat wastewater.

This is contradictory to the previous results from literature described in chapter 2.10.5 which suggest seasonal or weather related trends. Some of these previous studies had been carried out under ideal laboratory conditions and are limited in their ability to replicate real life conditions. This illustrates the importance of a full-scale trial such as Stoneyford ICW.

The lack of correlation agrees with the findings from the stakeholder engagement that climate should be considered but is not deemed a significant variable in impacting ICW wastewater treatment performance. It should be noted however that these results do not account for time, maturity or other external factors such as plant growth, influent concentration, site disturbances or flow changes which may be impacted by climatic conditions.

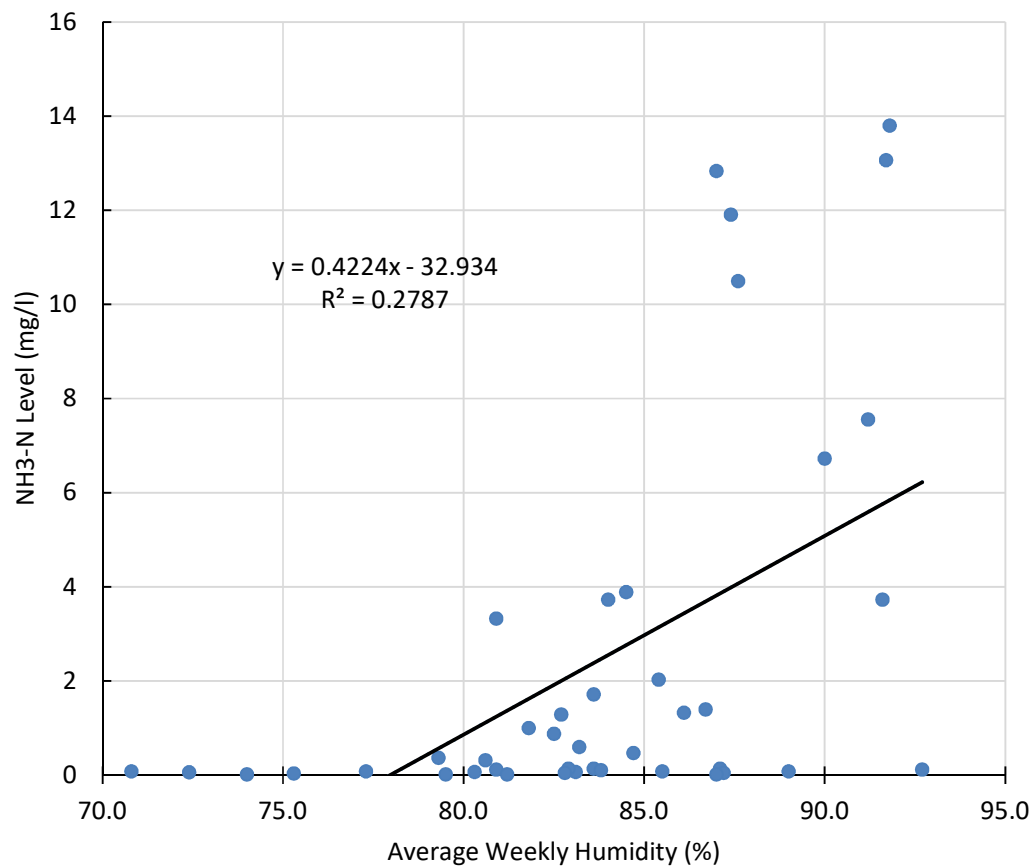


Figure 5.8 Discharge NH₃-N levels in relation to average weekly humidity.

5.3.4 Full Scale ICW Results Summary

This chapter has provided an analysis of the data collected from the full scale ICW system at Stoneyford. The data collected was correlated and observed to identify trends and interactions between the key variables discussed previously. Results indicated the following:

- there is evidence to suggest that Ammonia and COD performances are impacted over time, while BOD and SS were not;
- there is evidence to suggest that each of the ponds performed differently against the various contaminants with Ponds 1 and 2 typically less stable than Ponds 4 and 5, and Pond 3 performing differently for each of the contaminants;
- evidence suggests that performance of ponds 3, 4 and 5 in treating Ammonia and COD may be cyclical with reduced performance occurring at similar times each year (winter period);
- evidence suggests that an increased number of ponds will reduce the effects of high ammonia levels from earlier in the ICW system;
- comparisons of treatment within each pond could be used to determine retention times;
- weather and seasonal variations have little to no impact on the ICW ability to treat BOD, suspended solids, Ammonia or COD.

5.4 Pond 1 Issues

When analysing the results of the ICW, it is important to consider the following issues that arose. Despite being designed and constructed to have a level floor bed, some of the ponds showed evidence of an uneven bed which caused flooding in some areas as illustrated in Chapter 6. This was particularly apparent in Pond 1 where a variable water depth was apparent. Figure 5.9 illustrates the topographical survey of Pond 1 which demonstrates the different levels of the pond bed and areas of deeper water. This was confirmed when Pond 1 was drained for weir maintenance.

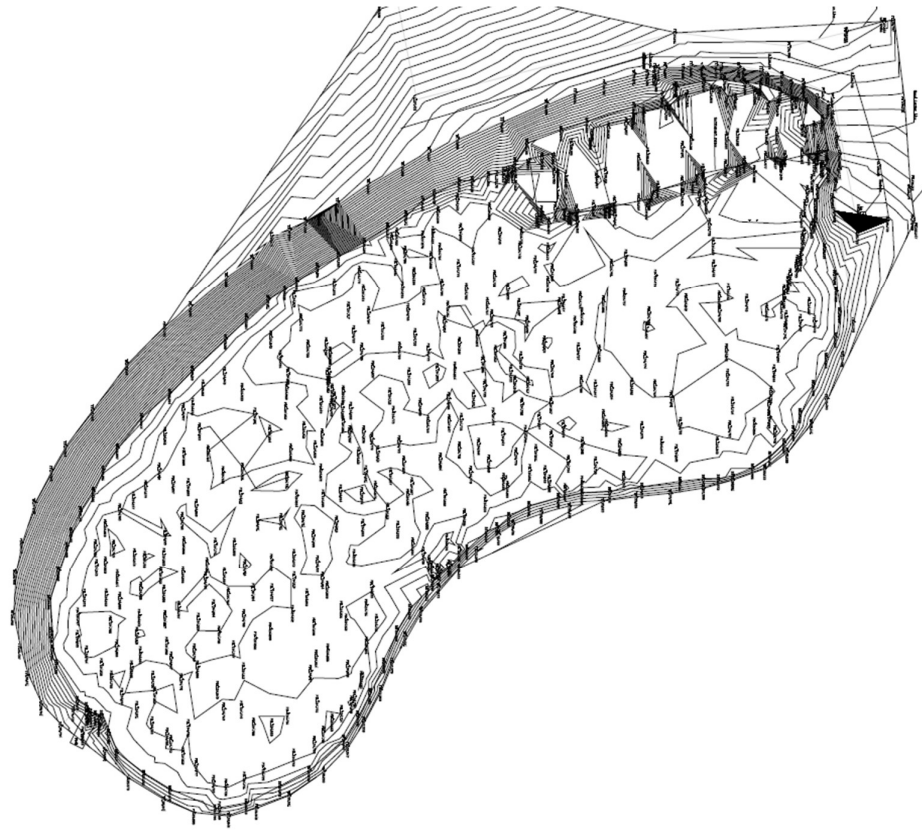


Figure 5.9 Pond 1 Topographical Survey (drawing provided by BSG Civil Engineering).

Pond 1 may have been influenced by water from previous field drains or stream. A desktop study which outlines the site boundaries onto the Stoneyford Ordinance Survey Map 5th Edition (Figure 5.10), demonstrates that a stream once flowed through the area where Pond 1 is now located. This stream is not identifiable on more recent OS maps. Another viable reason could be due to disruption of the pond bed during the construction of the Test Rig as described in Chapter 3.

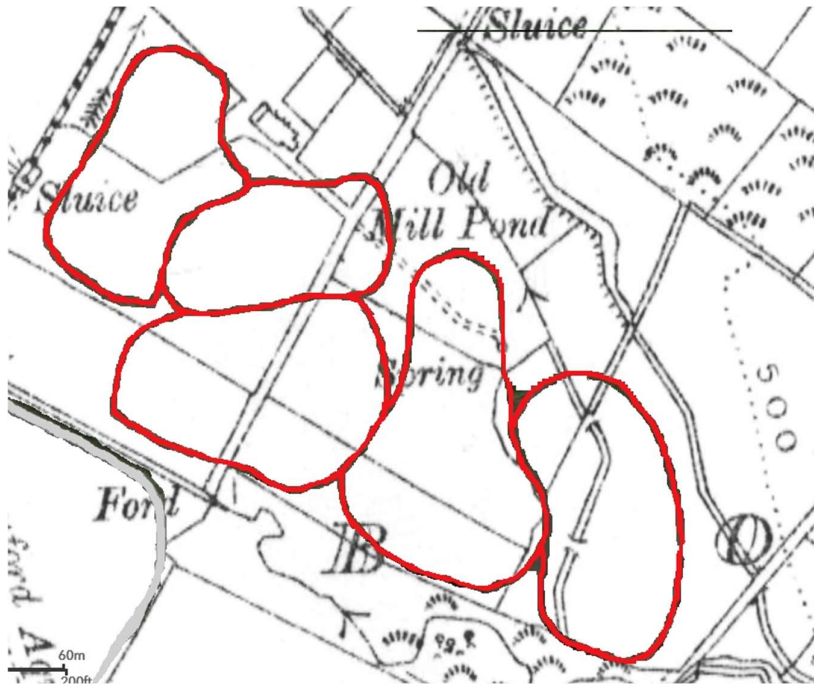


Figure 5.10 Outline of Stoneyford on Stoneyford Historical OS Map 5th Edition (PRONI, 2017).



Figure 5.11 Drying and clogging in Pond 1 during April 2017.

The flow from the sludge Pond into the wetland was inconsistent at best; as described in Chapter 7, the flow showed large differences between days. This caused issues with clogging,

especially during periods of dry weather as illustrated in Figure 5.11. This shows areas of deep water around the edges of Pond 1 and most of the Pond bed to be above water level. NIW decided to address the issues in Pond 1. Works began in July 2017 to drain the pond and lower the weir by 500mm. This would allow for a more consistent water level of <250mm to be reached as suggested by the design guidance (Figure 5.12).



Figure 5.12 Lowering of Pond 1 weir to reduce water level July 2017.



Figure 5.13 Completed weir at Pond 1 outlet allowing shallower water in Pond 1 August 2017.



Figure 5.14 Plant disruption in Pond 1 after TR construction May 2017.



Figure 5.15 Regrowth of Pond 1 vegetation after remediation works in August 2017.

As a result of the works being completed (Figure 5.13), the plants at the TR within Pond 1 regrew and flourished within a matter of weeks. Figure 5.14 illustrates the area of surface water in Pond 1 at the TR in May 2017 Figure 5.15 illustrates the regrowth of plants within Pond 1 in August 2017 where no surface water is visible.

This evidence illustrates how quickly the ICW can return to a fully vegetated area when such issues are remediated. This highlights their ability as living systems to recover and redevelop into fully functioning wastewater treatment systems once again.

5.5 Stoneyford Small-Scale Test Rig Results

As discussed within the literature review, the design of constructed wetlands has been researched and studied since the 1960s using various test beds, full scale systems and laboratory studies. However, the author is not aware of any studies which review the design principles of ICWs treating domestic wastewater in an outdoor environment.

This chapter details findings from a small-scale Test Rig designed by the author to test the design principles of an ICW in treating domestic wastewater at Stoneyford ICW. This chapter details the results collected over a 9 month period from August 2016 to April 2017. The sampling stopped after 9 months to accommodate for the draining of Pond 1 for the weir maintenance. The chapter considers the flow of wastewater at the inlet and outlet of each test bed. The chapter also compares water quality analysis of each of the test beds against the investigated design parameters of surface area and wastewater depth.

Water samples were taken from the outlets of each of the ponds on a weekly basis and analysed on the four main indicators of water quality of concern to Northern Ireland Water; BOD, suspended solids, Ammonia ($\text{NH}_3\text{-N}$), and COD. Data tables for each of the contaminants are available in Appendix F.

5.5.1 Flow Rate between Each Bed

This section considers the flow levels taken at the inlet and outlet of each bed to highlight the flow within each. A 10-way splitter chamber was used to ensure that each of the 8 beds within

the TR received equal flow of influent. The inlet and outlet flow rates of Test Beds 1 – 7 are illustrated in Figure 5.16.

Figure 5.16 illustrates that although the inlet levels entering each of the beds is similar, there are fluctuations with inflow and outflow. This may suggest that each bed did not receive equal amounts of wastewater during the study period. Or the stream identified in 5th edition Ordnance Survey Map / old field drains may have influenced the data.

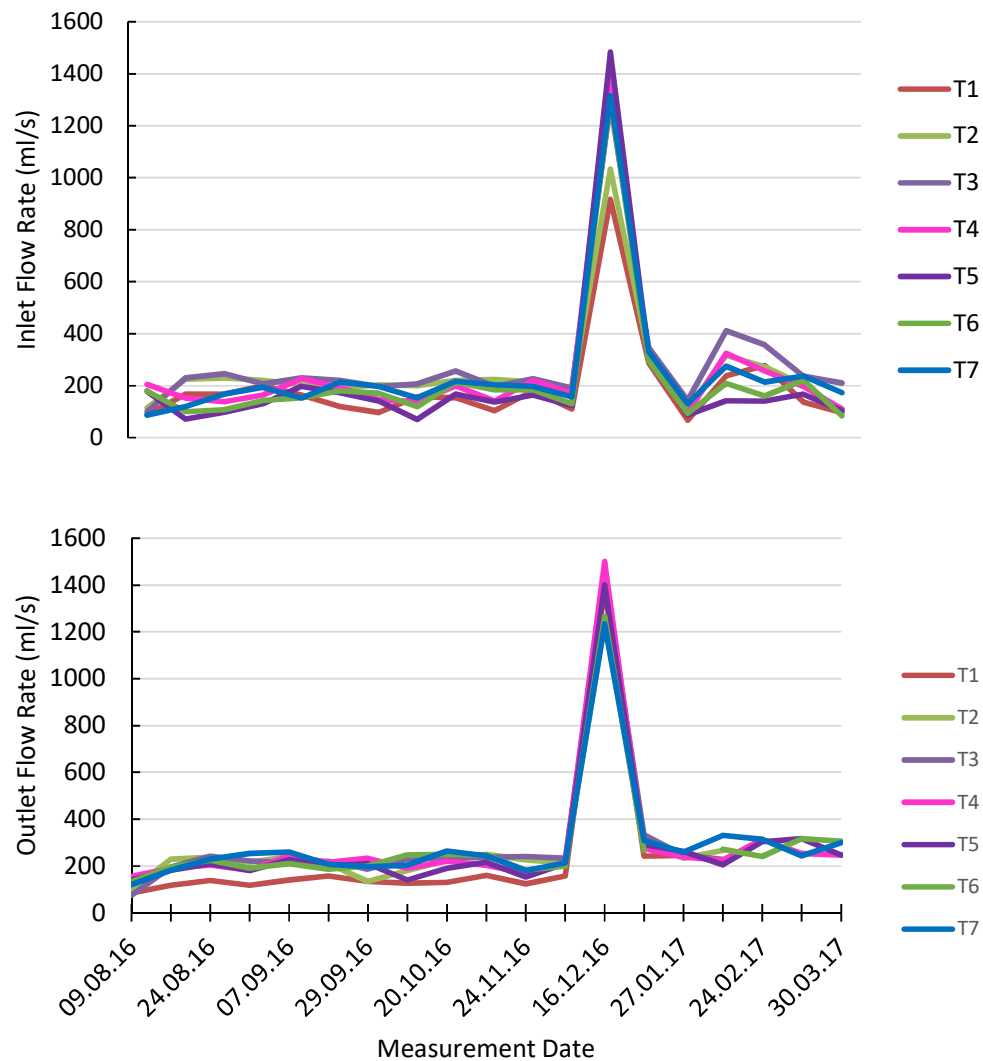


Figure 5.16 Inlet and Outlet rate per Test Bed.

To ensure that this was not due to a fault in the 10-way splitter chamber, an investigation was carried out to establish if the level within the chamber was correct and consistent. Using a spirit level, the levels were measured across all the chambers and found to be consistent as shown in Figure 5.17.



Figure 5.17 Measuring the level of the splitter chamber.

One explanation suggested by consultation at NI Water that could be used to explain the uneven flow would be the velocity and direction of the flow entering into the chamber. If the velocity is high entering into the chamber from the side of the chamber, it will create a spin in flow as it is forced upwards before allowing to flow into each of the 10 chambers. This will result in a preferential flow for the influent, causing some of the chambers to receive more than others. The large spike of flow measured on the 16th December 2016 corresponds with a heavy fall of rain at 21mm on that day. This would cause an increase of flow from the sludge ponds and the splitter chamber into the test beds and would subsequently increase the flow from the outlet as seen in Figure 5.16.

Figure 5.16 illustrates that outlet levels showed a similar pattern to inlet levels across the sampling period, but in some cases the amount of flow exiting the pond is higher than what is entering through the inlet. This could be due to the following reasons:

- Inlet flow did not account for any precipitation that may have fallen into the test beds that may have caused an increased outlet rate;
- Inlet rates were heavily influenced by the turning on of the influent pump into the sludge ponds; if an inlet flow was measured after the pump had been turned off, the rate would be relatively low in comparison to the outlet flow which will have some degree of retention.

Overall, it can be seen that inlet and outlet levels, although similar, were not equal and may have influenced the test rig investigations. Although there is no evidence to suggest that the changes in flow had any direct impact on the test bed performances.

5.5.2 Performance of Each Test Bed over Time

This section illustrates the results in relation to the water quality performance of each of the test beds within the TR over the duration of the sampling period of 9 months to determine if there are any notable differences in treatment performance. The performance for this section was based on the difference in concentration of each contaminant between the Inlet levels and the discharge at the end of each pond (outlet).

Test bed H1 was used to represent a HSSF system and is of different design parameters than T1 – T7. It is hoped that this section will provide an understanding of how the HSSF performs against the different design parameters of the ICW when built to the same scale and treating the same wastewater influent.

However, it must be noted that the water depth of H1 was altered throughout the study period to determine the impact of water depth within the HSSF on treatment performance. Although the water depths being tested were within the suitable range for effective treatment within HSSF design and should not impact treatment ability, the changes in depth should be considered when analysing HSSF performance against the other test beds which have a more uniform water depth over the duration of the study.

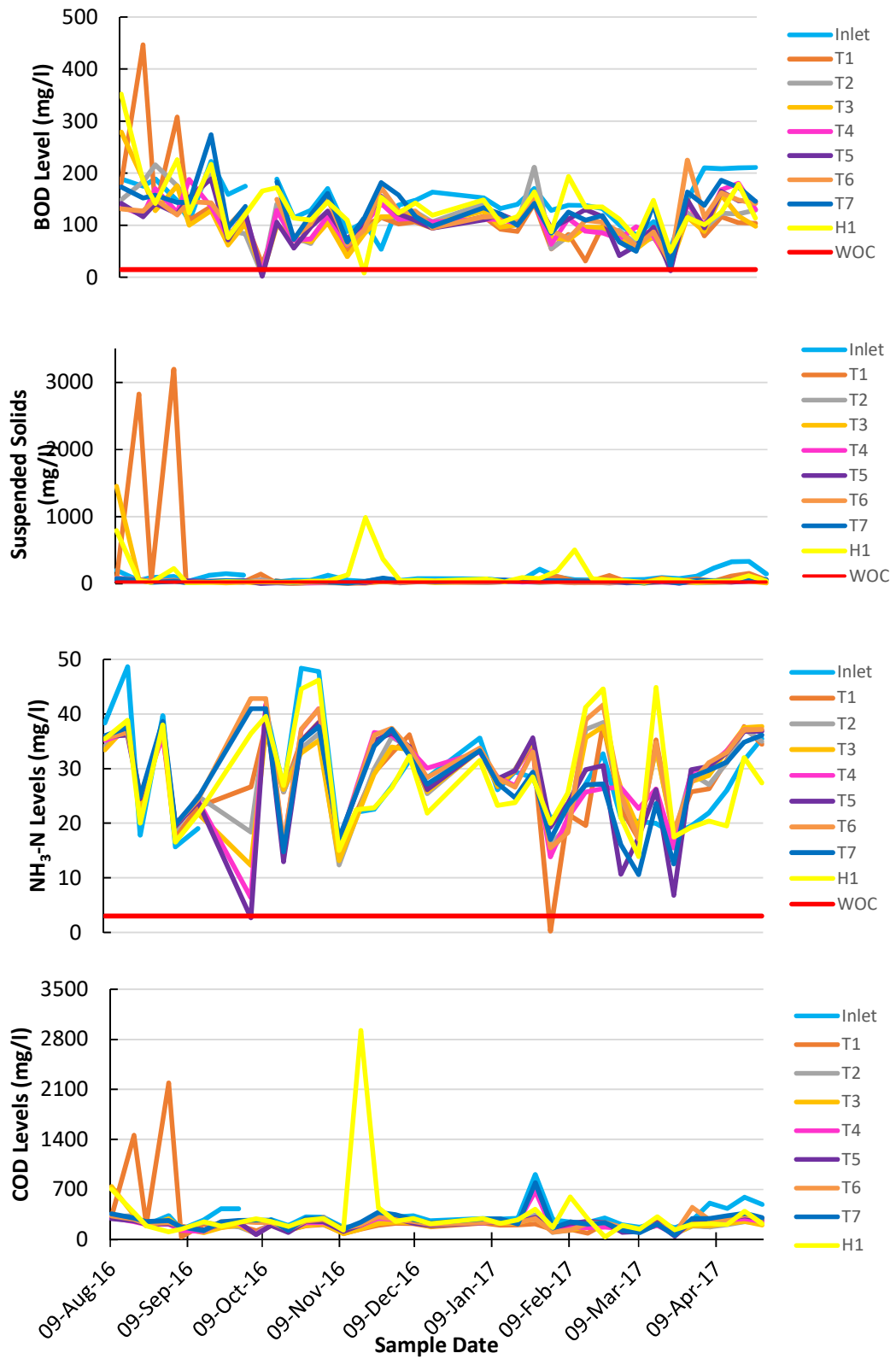


Figure 5.18 Outlet water quality between test beds over time.

Figure 5.18 illustrates the water quality results at the outlet of each of the test beds over the 9 month test period. Results show that for BOD removal the test beds followed similar patterns throughout the study. Suspended solids results show that most of the beds follow similar trends, although T1 and H1 show large spikes.

For ammonia, the results again show similar trends with all test beds apart from October 2016 when a clear difference in performance can be seen. COD results are similar to suspended solids in that all beds follow the same trends with T1 and H1 showing spikes in levels.

Test beds T1-T3 performed better than other beds for BOD, suspended solids, and ammonia removal while T4 and T5 showed similar neutral results. For COD performance however, T4 and T5 performed the best, followed by T1-T3. Test beds T6, T7 and H1 consistently performed more poorly than the other beds for all of the treatments tested.

5.5.3 Water Quality over Surface Area

This section illustrates the results in relation to the water quality performance of each of the different pond surface areas of 40m², 60m² and 80m² to determine if the design rule of thumb of 20m² – 40m²pe is appropriate. The performance for this section was based on the performance of each of the different surface areas in treating the four main contaminants.

The test beds are split into 2 groups; 3 of which are set at a water depth of 50mm and 3 are set at a water depth of 250mm. This allows for a comparison of each surface area within different water depths to allow for a better understanding of the impacts of volume on performance.

The results from each of the contaminants will be illustrated in turn, with a combined summary of overall performance over time given at the end.

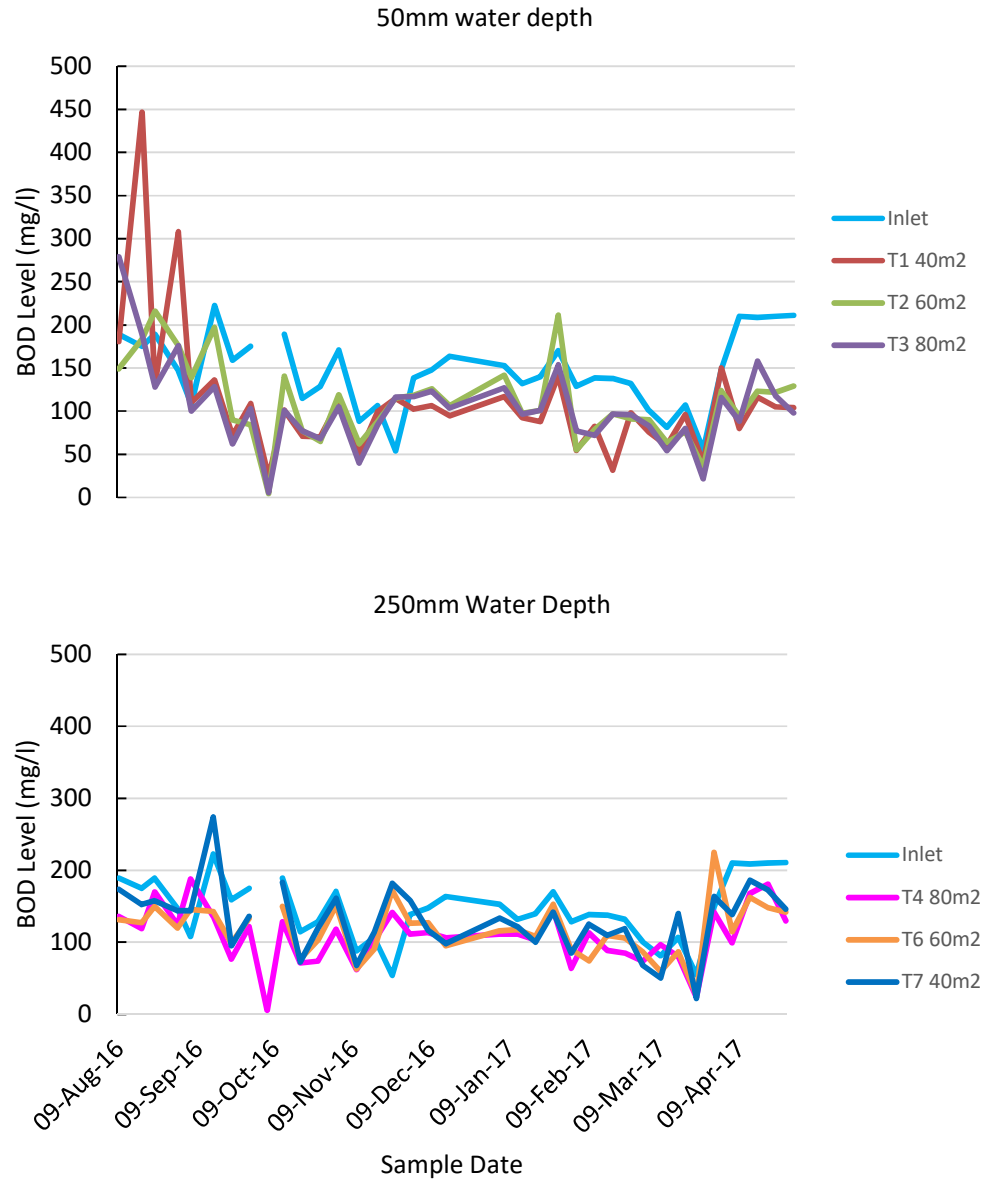


Figure 5.19 BOD surface area comparison at 50mm and 250mm water depth.

Figure 5.19 shows the BOD performance comparisons between the test beds of different surface areas at different water depths. T3 typically performs better than T2 but only outperforms T1 for around half of the study. This would suggest that at a water depth of 50mm, there was no significant difference in wastewater treatment at the different surface areas, however the larger surface area tended to be the most effective over the study duration.

With regards to 250mm water depth, all beds show very similar trends with T6 tending to be more stable than T4 with a narrower range of fluctuation. However BOD levels are typically higher in T6 than T4 suggesting that stability of water treatment has not improved the beds ability to treat BOD. T7 also illustrates a similar trend to T6, although has typically higher BOD levels. Overall it can be concluded that surface area has a small impact on the Test Rig's ability to treat BOD, with the larger areas typically being more effective, especially when water depth is high. However, the differences are marginal.

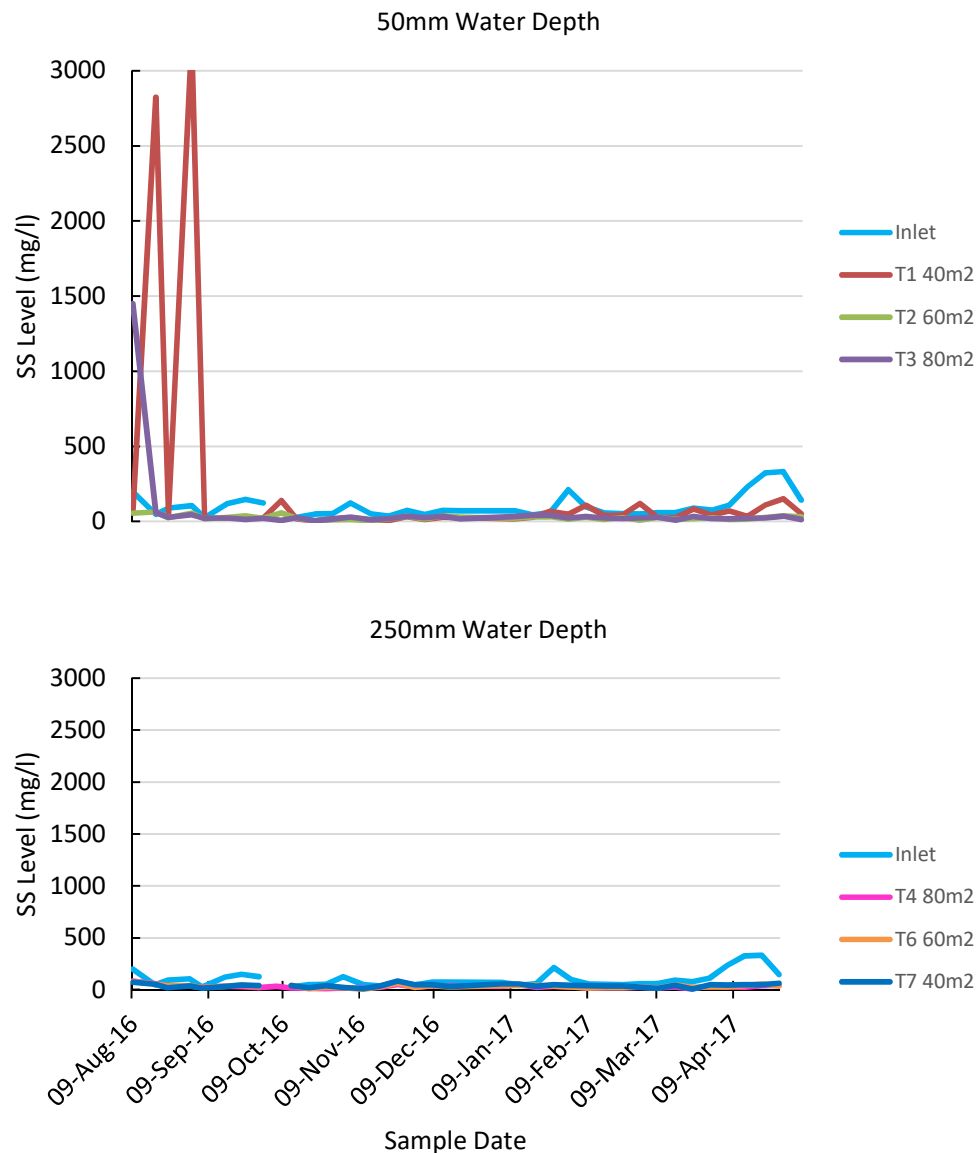


Figure 5.20 SS surface area comparison at 50mm and 250mm water depth.

Figure 5.20 shows the SS performance comparisons between the different surface areas at different water depths. T3 demonstrated a more consistent level of performance throughout the study, although T2 was similar in SS treatment despite having less water treatment stability. T1 showed very high fluctuations across the study and was typically higher throughout, although SS levels did show good performance during certain times. This would again suggest that the higher surface area of 80m² was more effective in SS removal than the smaller 60m² and 40m² test beds when set at a water depth of 50mm. At a water depth of 250mm T4 shows a stable SS removal with typically lower levels being recorded. T6 and T7 all show very similar patterns and SS levels, with T7 underperforming in comparison to the others towards the end of the study. Overall it can be concluded that surface area has a small impact on the Test Rig's ability to treat SS, with the larger areas typically being more effective, especially when water depth is high.

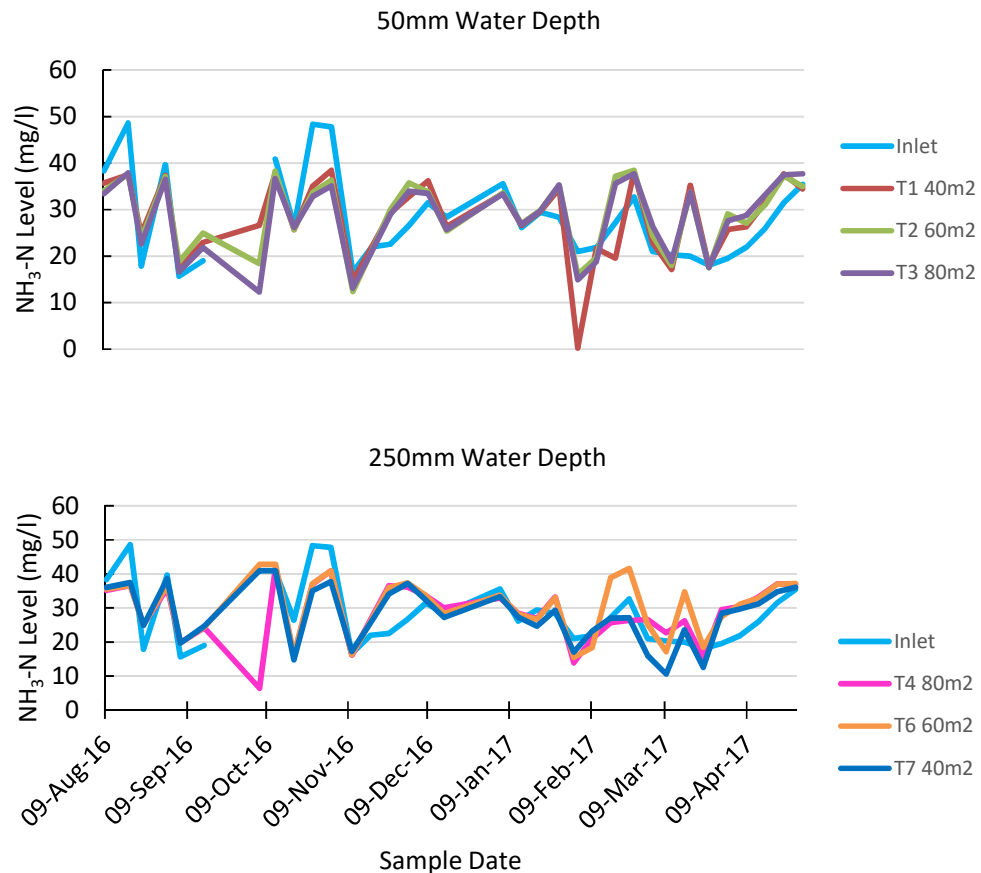


Figure 5.21 NH₃-N surface area comparison at 50mm and 250mm water depth.

Figure 5.21 illustrates the $\text{NH}_3\text{-N}$ performance comparisons between the 3 different surface areas at different water depths. T1 levels fluctuate greatly over the study period although levels are typically within a slightly narrower range than the inlet with a large decrease in levels to 0.24mg/ in February. T2 and T3 levels are almost the same as T1 with lower levels of $\text{NH}_3\text{-N}$ being recorded in October. T4 demonstrates the lowest $\text{NH}_3\text{-N}$ results recorded in October, although results are generally very similar to T6 and T7 for the remainder of the study, with T6 underperforming towards the end of the study. Overall it can be concluded that surface area has a small impact on the Test Rig's ability to treat $\text{NH}_3\text{-N}$, with the larger areas typically being more effective. However, this change is very slight when at higher water depths.

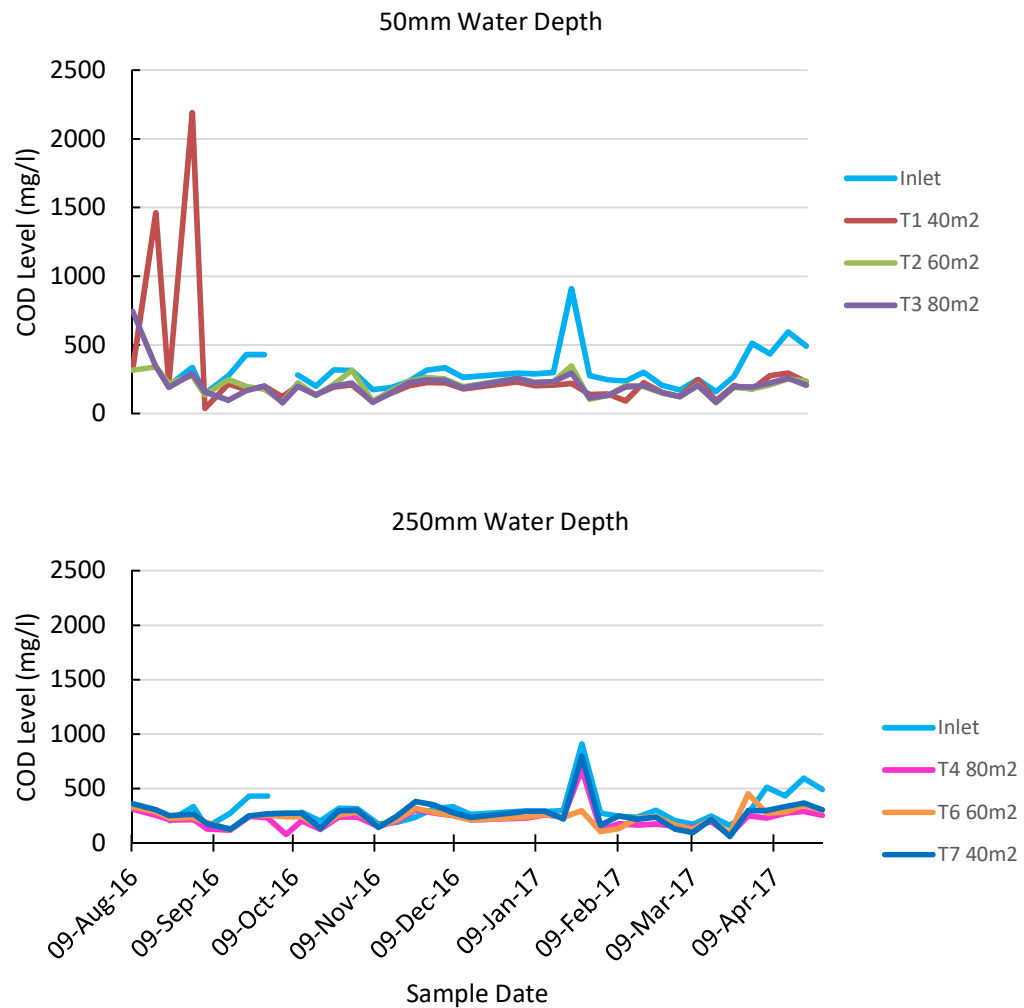


Figure 5.22 COD surface area comparison at 50mm water depth.

Figure 5.22 shows the COD performance comparisons between the different surface areas at different water depths. T1 shows very high spikes of 1460mg/l in August and 2190mg/l in September, before stabilising below the inlet levels for the remainder of the study. T2 however is much more stable, remaining below the inlet levels consistently over the study period, although typically tends to record higher levels than T1 after September. T3 COD levels begin high at 342mg/l, however they quickly stabilise and follow a similar but lower pattern to T2, although slightly higher than T1.

T4 shows typically lower COD levels than the other beds throughout the study, although T6 tends to perform better during middle of the study with T7 showing the highest levels in January of 796mg/l. Again, it can be concluded that surface area has a little impact on the Test Rig's ability to treat COD, with the larger areas being slightly more effective. However, this change between 60m² and 80m² is very slight when at higher water depths.

5.5.4 Water Quality over Water Depth Comparisons

This section aims to illustrate the results in relation to the water quality performance of each of the different water depths of 50mm, 150mm and 250mm in order to determine if the design principles of having no less than 50mm of water and no more than 250mm of water depth were appropriate.

The performance for this section was based on the performance of each of the different water depths of the three 80m² test beds in treating the four main contaminants. The results from each of the contaminants is illustrated in Figure 5.23.

For BOD performance the test beds show similar patterns of fluctuations across the 9 month test period. T3 typically showed the lowest figures across the testing, whereas T4 and T5 showed similarly higher levels. This would suggest that at a surface area of 40m² pe, the shallower water depth of 50mm was more effective in removing BOD.

SS performance results appears much more stable across the 9 month test period with the exception of T3, which had very high levels at the beginning of testing. T3 again tends to show typically lower figures across the testing, whereas T4 and T5 showed similar patterns that were slightly higher in levels. This would suggest that at a surface area of 40m² pe, the shallower water depth of 50mm was more effective in removing SS.

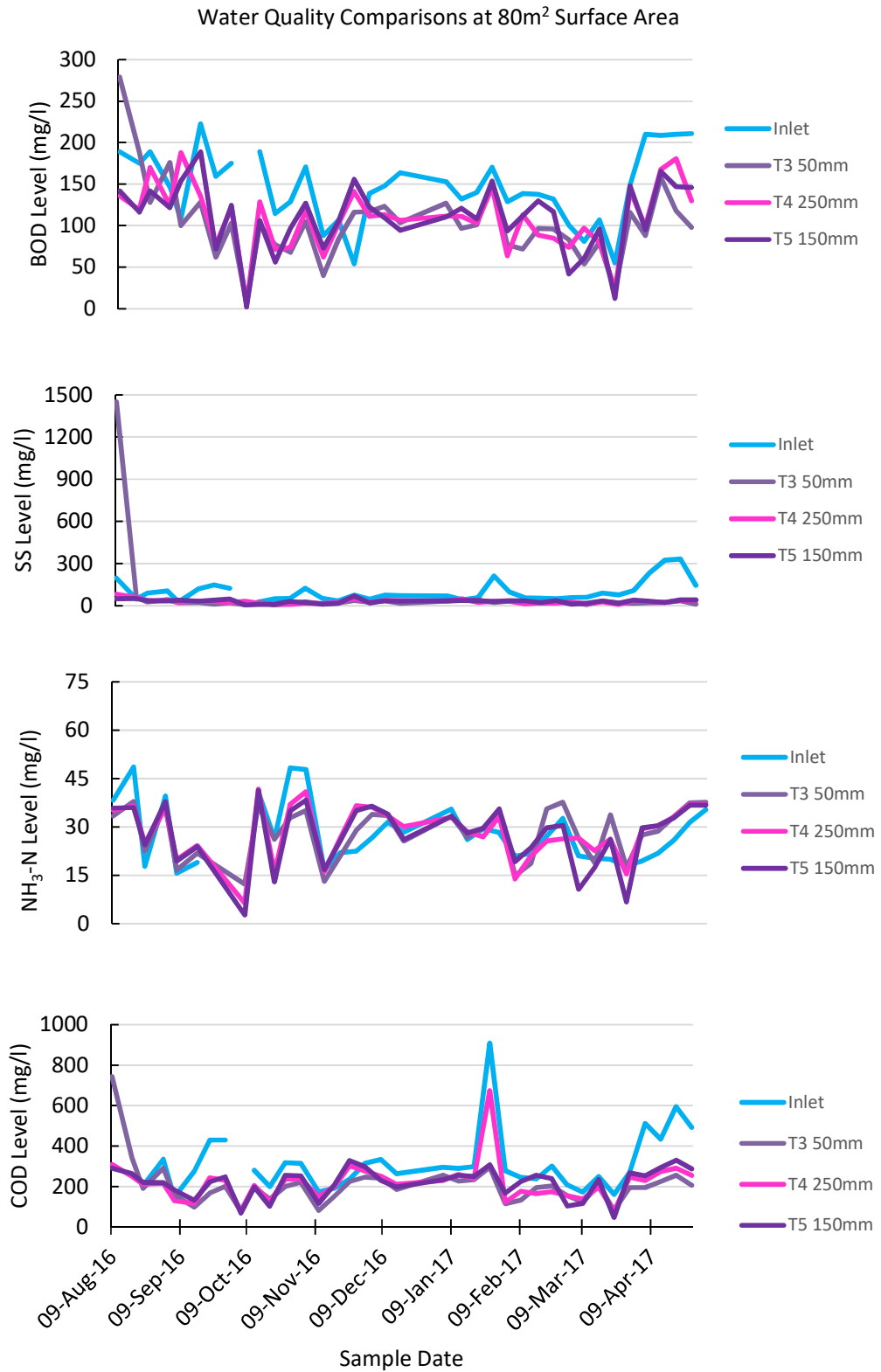


Figure 5.23 Water Quality comparisons at 80m² surface area.

In terms of ammonia performance, all test beds again show similar patterns of fluctuations across the 9 month test period; however, there is no water depth that performs consistently lower than the others, which would suggest that water depth has little to no impact on $\text{NH}_3\text{-N}$ removal at this scale. T3 and T4 showed similar performances, with T4 showing higher levels at the beginning of the study and T3 showing higher levels at the end.

T5, despite showing similar patterns, was much more consistent in results, which would suggest that a water depth of 150mm could be the most effective in treating $\text{NH}_3\text{-N}$ at an area of 40m^2 pe in the long term, although results were again not significantly different than the other water depths.

5.5.5 Horizontal Bed Performance against Depth Variances

This section illustrates the results in relation to the water quality performance of the HSSF bed under the different water levels to determine how it performs under each of the different ratios of soil and gravel to water. This was achieved by changing the water depth between surface level 0mm and 200mm beneath the surface across the period of 9 months. The performance for this section is based on the performance of each of the different water depths in treating the four main contaminants. The results from each of the contaminants are displayed on one graph with water depth displayed on a second axis so that a comparison between contaminants and connection to water depth could be made. Results are illustrated in Figure 5.24.

Figure 5.24 illustrates the impacts of changing water depth on the four main contaminants of BOD, suspended solids (SS), Ammonia ($\text{NH}_3\text{-N}$) and COD over the test period of 9 months. BOD levels fluctuated over the 9-month period but showed no real relationship to changes in water depth at any stage. Suspended solids on the other hand showed consistent changes in relation to water depth; as the water level decreased below the surface of the HSSF, suspended solids increased and when water levels rose again, suspended solids levels decreased.

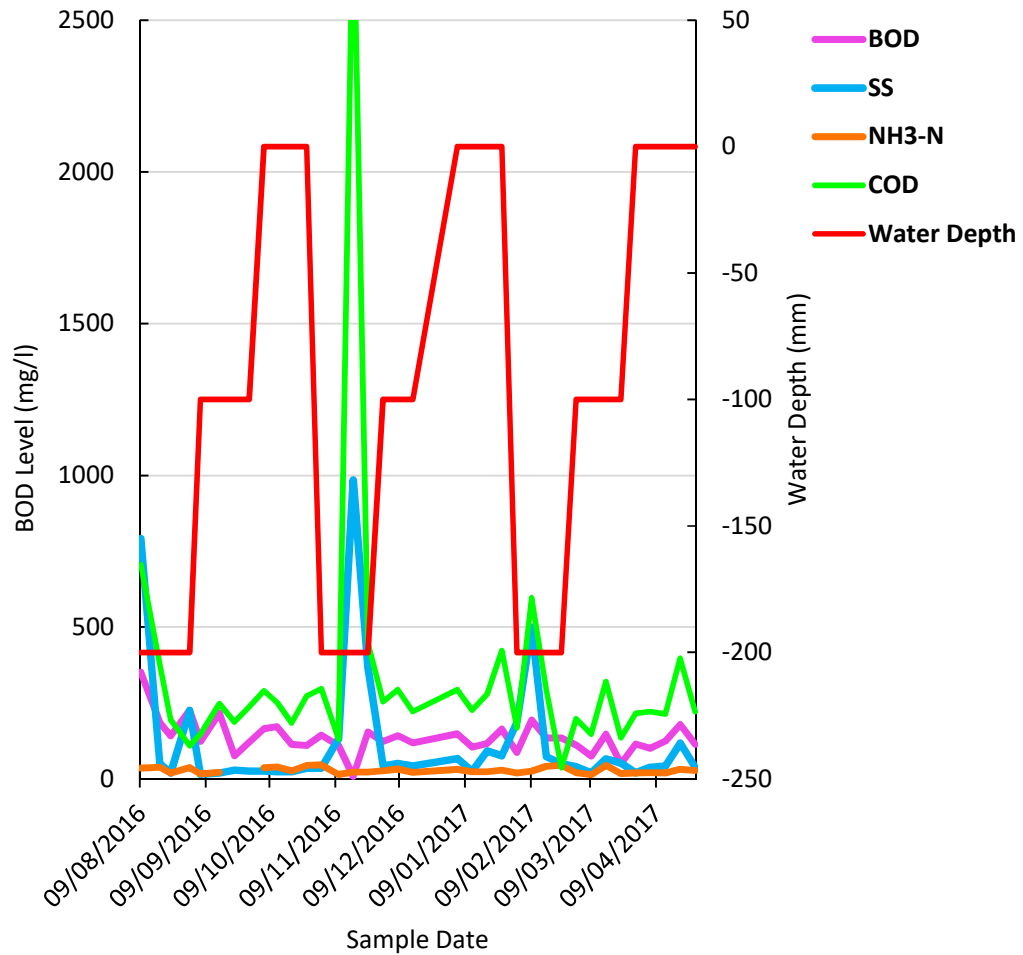


Figure 5.24 Water Depth vs Water Quality within a HSSF Test Bed.

This would suggest that having a higher water level within the HSSF is more effective in treating suspended solids than having a lower water level. Ammonia levels within the HSSF remained consistent throughout the study and showed no reaction to changing water depths within the HSSF. Conversely, COD reacted much like suspended solids and increased greatly when water levels were decreased and decreased when water levels rose again. Thus, this would again suggest that having a higher water level within the HSSF is more effective in treating COD than having a lower water level.

5.5.6 Test Rig Results Summary

This chapter has provided an analysis of the data collected from the small scale TR system at Stoneyford. The data collected was compared and observed to identify trends and interactions between the key variables discussed previously. Results indicated the following:

- test beds performed differently in the removal of various contaminants with T1-T3 performing better than other beds for BOD, suspended solids, and ammonia removal while T4 and T5 performed better for COD. Test beds T6, T7 and H1 consistently performed weaker than the other beds for all of the treatments tested;
- evidence suggests that a change in surface area between 40m^2 – 80m^2 has very little impact on the wetlands ability to treat wastewater although the larger surface areas did tend to be slightly more effective;
- evidence also suggests that a change in water depth between 50mm – 250mm has little impact on the wetlands ability to treat wastewater although the shallower water depth of 50mm did tend to be more effective than the deeper ponds;
- decreasing the water level of a HSSF from surface level 0mm to 200mm beneath the surface had little to no effect on BOD or ammonia treatment although there was a significant correlation between water levels within the HSSF and the levels of suspended solids and COD.

5.6 Drone Study Results

The use of drones for monitoring vegetation is not new. Previous studies have identified the benefits of monitoring vegetation from an aerial view for various applications such as forestry (Lisein, J., et al., 2014), agriculture (Mesas-Carrascosa, F., et al., (2015); Miller, E., et al., (2017)) and aquatic plants (Husson, E., et al., 2016; 2017). However, the use of a drone to monitor vegetation within a constructed wetland is an innovative method of measuring performance. This chapter considers flying a drone over the ICW system at Stoneyford to determine whether it is possible to model vegetation change with time and ICW treatment performance. The methods are described in Chapter 5 and Appendices B and C. This produced two types of data for analysis. These were over-head photographs which were analysed using Image Pro Software to quantify changes in vegetation growth. Videos were recorded and then analysed

using Zephyr Arial software to create 3D models of each pond to determine whether the volume of vegetation could be determined. An aerial image of the site taken from Pond 5 using a drone is shown in Figure 5.25.

Photographs of each pond were taken during site visits in December 2016, February 2017, April 2017 and July 2017. The photographs were taken by the drone flying at an altitude of 120m. This allowed the entire pond to be included in a single photograph. Photographs for each pond are shown in Figures 5.26 – 5.30. These show how the vegetation in each pond changed during this 7 month period. Video was recorded during the visits in December 2016, February 2017 and April 2017 for 3D modelling.



Figure 5.25 Aerial image of site from Pond 5.



Figure 5.26 Time Sequence Images of Pond 1 from December 2016 to July 2017.

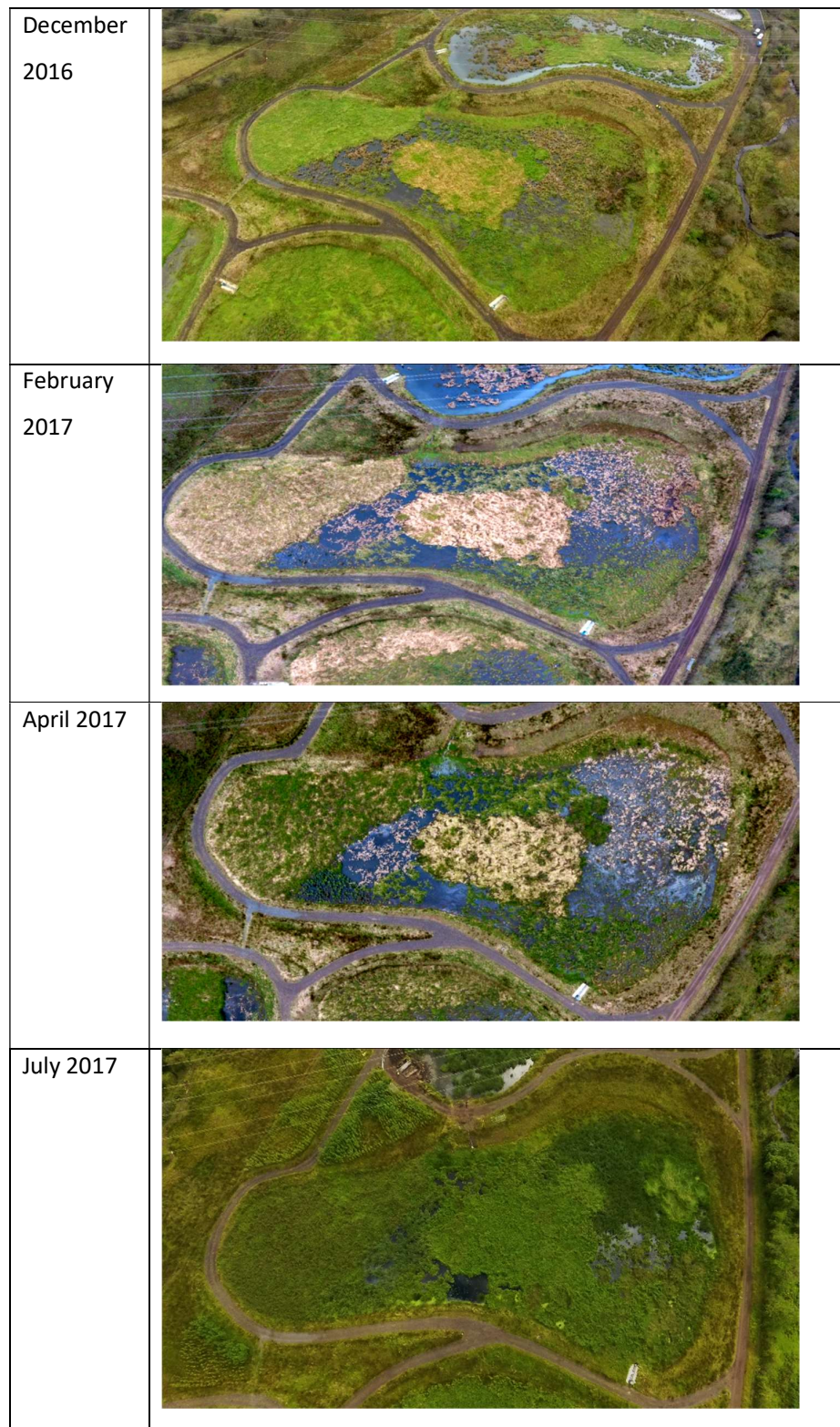


Figure 5.27 Time Sequence Images of Pond 2 from December 2016 to July 2017.

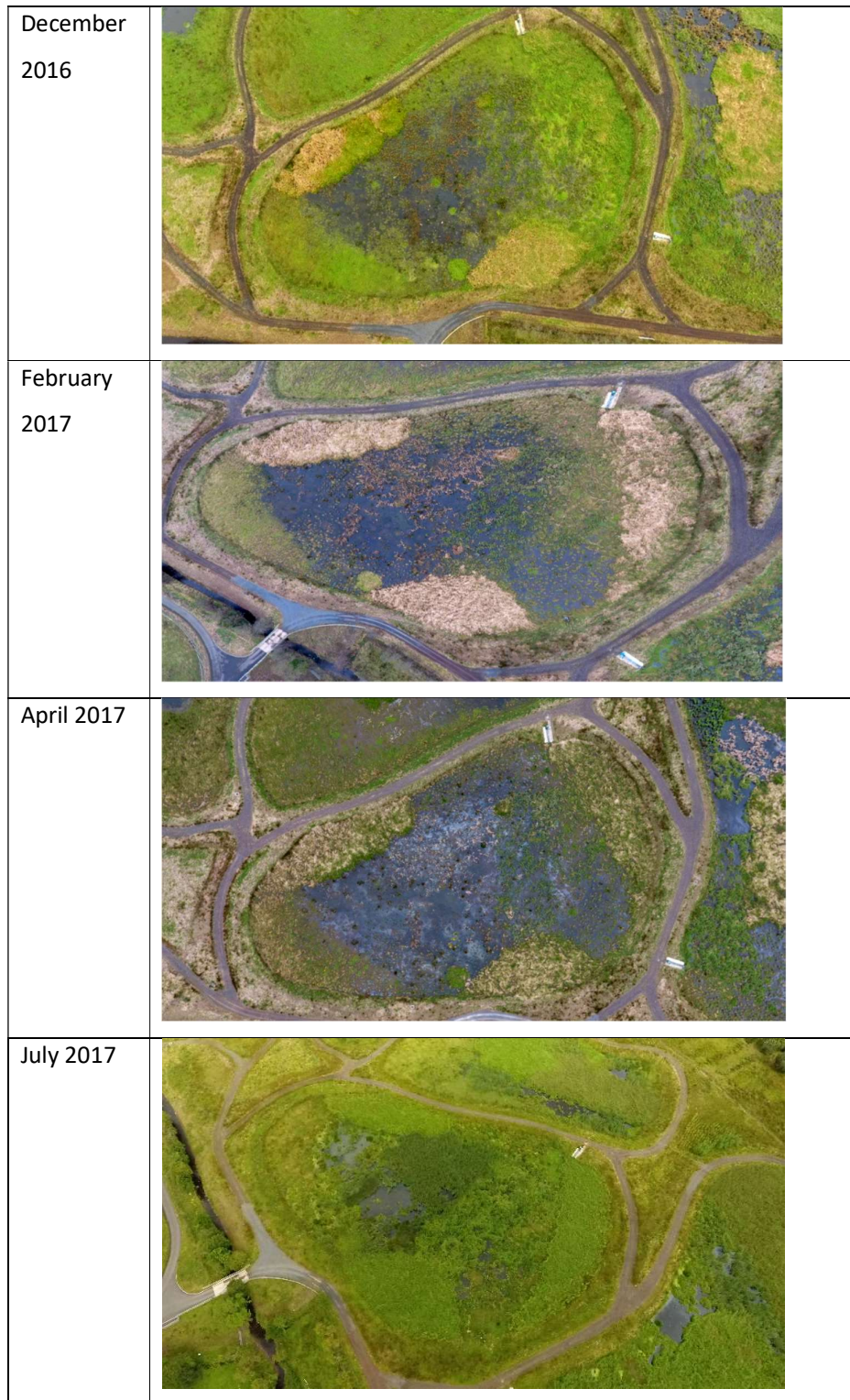


Figure 5.28 Time Sequence Images of Pond 3 from December 2016 to July 2017.

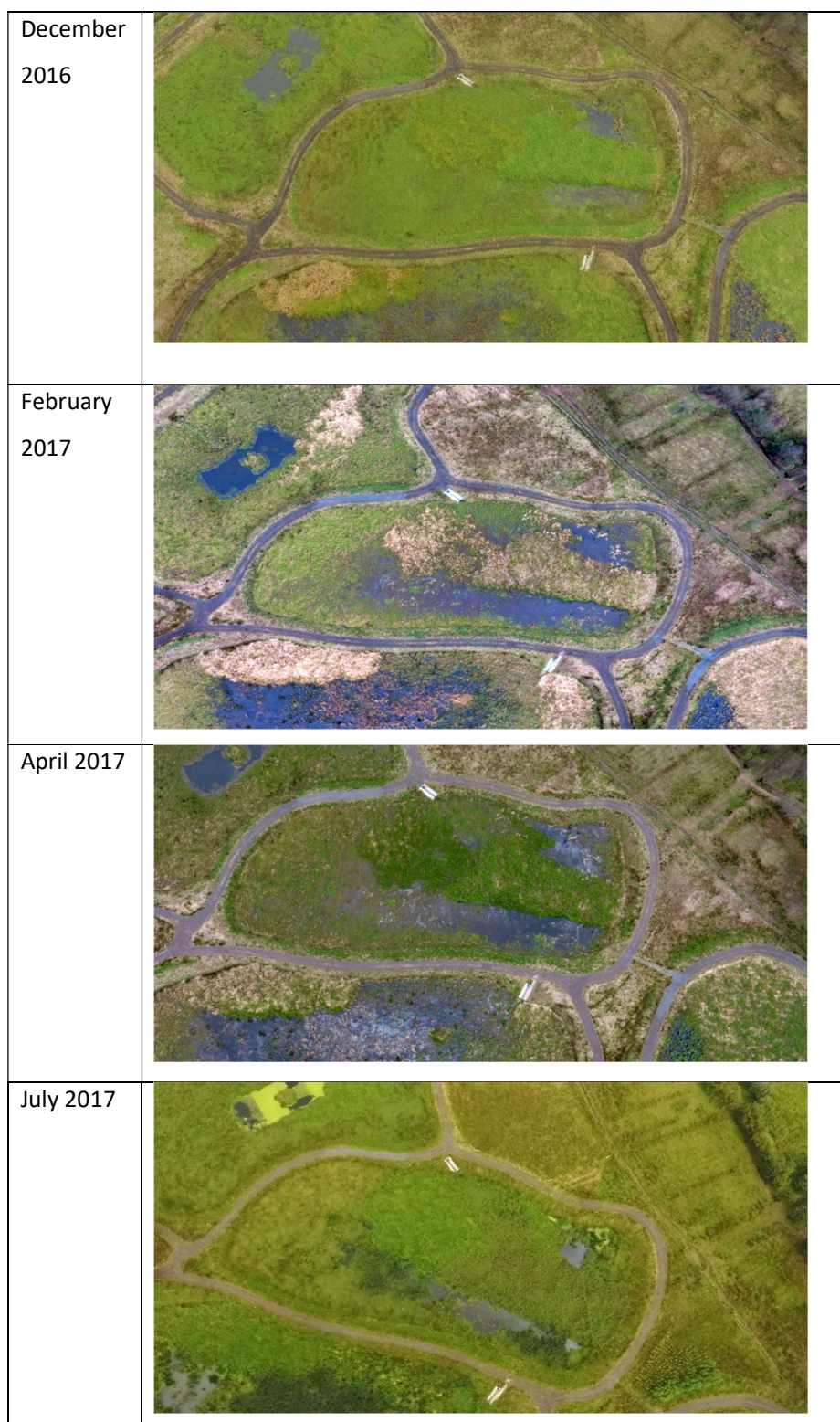


Figure 5.29 Time Sequence Images of Pond 4 from December 2016 to July 2017.





December 2016		
February 2017		
April 2017		
July 2017		

Figure 5.30 Time Sequence Images of Pond 5 from December 2016 to July 2017.

5.6.1 Comparison of Aerial Photograph with Planting Plan

Figures 5.31 – 5.35 illustrate the planting plans for each of the 5 ICW ponds. These figures can be compared with the aerial images of each of the 5 ponds in Figures 5.26 – 5.30. This comparison allows for areas of planting to be correlated with individual plant species.

Key:

- GM (*Glyceria maxima*),
- TL (*Typha latifolia*),
- IP (*Iris pseudacorus*),
- TA (*Typha angustifolia*),
- CR (*Carex riparia*),
- M (mix of appropriate species as listed in Chapter 3)

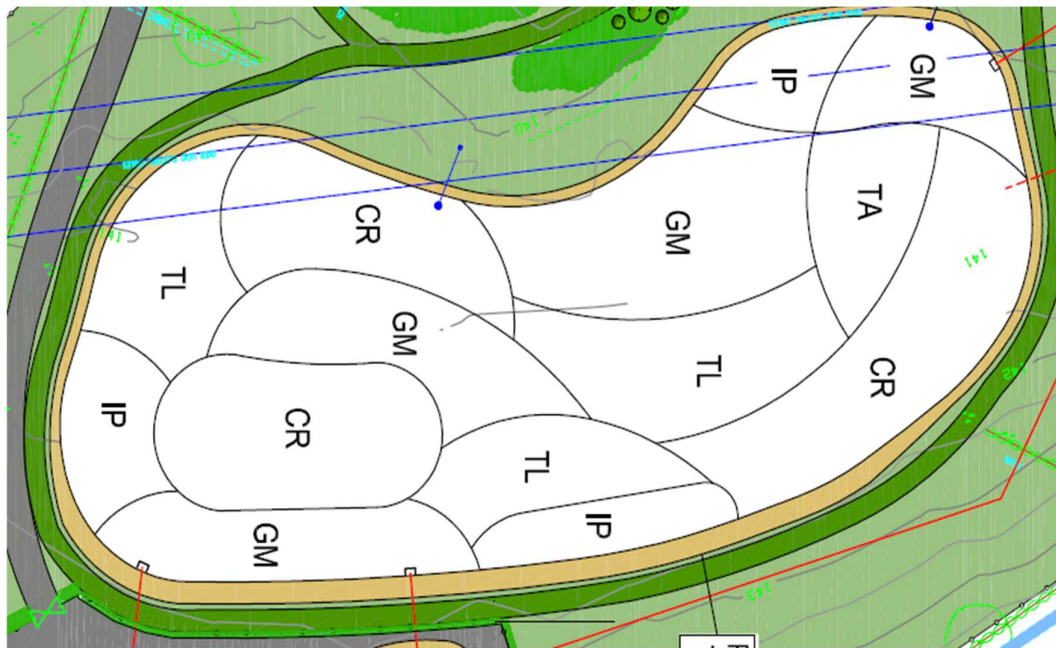


Figure 5.31 Pond 1 planting plan.



Figure 5.32 Pond 2 planting plan.

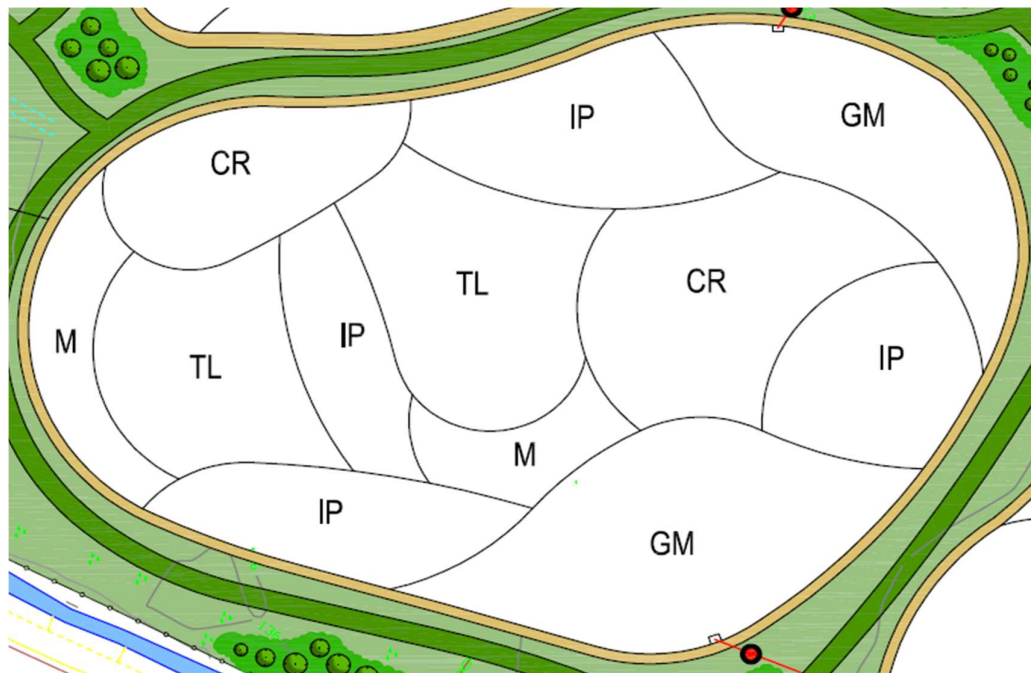


Figure 5.33 Pond 3 planting plan.

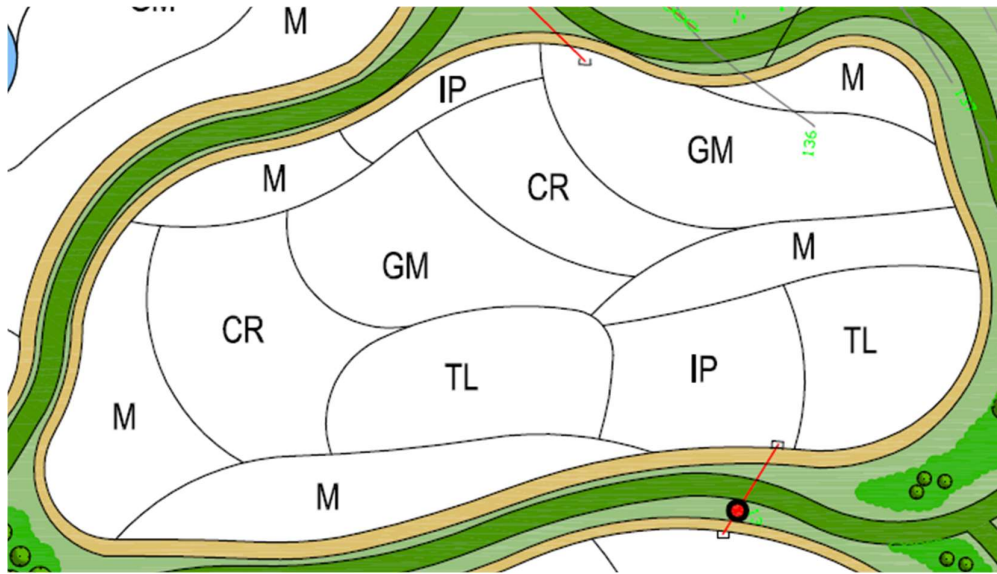


Figure 5.34 Pond 4 planting plan.



Figure 5.35 Pond 5 planting plan.

Comparison of Figures 5.31 – 5.35 with Figures 5.26 – 5.30 illustrates that *Glyceria maxima* remains present within all the ponds across seasons with die back in winter. *Typha latifolia* was more consistent than *Carex riparia* in Pond 1, however *Typha latifolia* showed significant die back during the winter in Ponds 2-4.

Iris pseudacorus and *Typha angustifolia* appeared to die back in Ponds 2 and 3 in winter. The Mix of species shows differences in seasonal distribution, which could be related to the densities of particular species within the mix of each of the ponds.

During the planting of the Test Rig it was proposed that established plants were extracted manually from Pond 1. This proved difficult due to their established root structure. The use of machinery was considered inappropriate as it would be difficult to select specific species. Thus, manual plant extraction occurred in September when the plants began to die back. The combination of late planting and unscreened influent hindered initial plant establishment.

5.6.2 Comparison of Pond Vegetation Area

The area of the ponds was calculated using the 2 methods described in Appendices B and C. Table 5.4 compares the design areas of each pond with area data from Google Earth Pro, Image Pro and 3DF Zephyr Aerial.

Table 5.4 Comparison of pond areas.

Pond	Area (m ²)				Difference from Original Design (%)		
	Original Design	Google Earth Pro	Image Pro (Average of 4 site visits)	Zephyr (Average of 4 site visits)	Google Earth Pro	Image Pro	Zephyr
Pond 1	7476	6860	7084	5493	-8	-5	-27
Pond 2	8301	9047	8252	10576	9	-1	27
Pond 3	8939	8588	7745	9362	-4	-13	5
Pond 4	5874	5836	5423	5973	-1	-8	7
Pond 5	6479	6424	6653	6904	-1	-3	7

Table 5.5 Pond area comparison between Image Pro analysis and Google Earth.

Pond	Date	Area (m ²)					% Difference between Image Pro and Google Earth
		Water	Green	Brown	Total (Image Pro)	Total (Google Earth)	
1	December	2126	2007	2519	6651	6860	-3
	February	1965	272	4848	7084	6860	3
	April	2916	1504	1961	6380	6860	-7
	July	389	6088	162	6638	6860	-3
2	December	2130	5837	285	8252	9047	-9
	February	1958	2996	3642	8596	9047	-5
	April	2147	3620	3354	9121	9047	1
	July	750	7504	457	8712	9047	-4
3	December	1867	4405	1696	7967	8588	-7
	February	2626	909	4210	7745	8588	-10
	April	3023	3205	1560	7788	8588	-9
	July	597	7324	117	8038	8588	-6
4	December	363	4689	372	5424	5836	-7
	February	1271	2792	1329	5393	5836	-8
	April	2300	1888	1405	5593	5836	-4
	July	357	4605	684	5645	5836	-3
5	December	271	5031	1450	6752	6424	5
	February	1091	4757	805	6653	6424	4
	April	1185	4922	903	7010	6424	9
	July	415	6567	12	6994	6424	9

The area data from Table 5.4 shows that the areas recorded using Google Earth Pro, Image Pro and 3DF Zephyr Aerial analysis was typically within 10% precision when compared to the original design. Google Earth Pro and Image Pro area analysis were within similar ranges to each other, confirming their accuracy. Ponds 2 and 3 however showed a difference of 27% between the Zephyr calculation and the original design, and over 20% difference between the Google Earth Pro and Image Pro analysis. This level of accuracy is deemed poor; however this should not diminish the credibility of the findings for the Zephyr analysis of Ponds 3 -5. The data collected illustrates that aerial photography using drones is effective for measuring wetland area.

A comparison of pond vegetation area over the 7 month period from December 2017 to July 2017 was carried out using Image Pro and Google Earth Pro. The drone image was subdivided into three areas i.e. water, green (healthy vegetation) and brown (decaying vegetation). These were combined to form a total area. The area measurement function in Google Earth Pro was used to determine the total area of each pond. This acted as a control to compare the accuracy of the Image Pro image analysis.

Table 5.6 Vegetation distribution over time using Image Pro analysis.

Pond	Date	Area (% of total pond area)			
		Water	Green	Brown	Total Vegetation
1	December	32	30	38	68
	February	28	4	68	72
	April	46	24	31	54
	July	6	92	2	94
2	December	26	71	3	74
	February	23	35	42	77
	April	24	40	37	76
	July	9	86	5	91
3	December	23	55	21	77
	February	34	12	54	66
	April	39	41	20	61
	July	7	91	1	93
4	December	7	86	7	93
	February	24	52	25	76
	April	41	34	25	59
	July	6	82	12	94
5	December	4	75	21	96
	February	16	71	12	84
	April	17	70	13	83
	July	6	94	0	94

Table 5.5 compares the areas obtained using the two methods described in Appendices B and C. This breaks down each pond into the area of water, green and brown. It compares the total area determined using Image Pro with that determined using Google Earth Pro. This shows the percentage difference between the two methods to be typically less than 7% with none greater than 10%.

The data in Table 5.5 shows how the water, green and brown areas for each pond change with time. The area of water, green and brown for each of 5 ponds from each of the 4 site visits was calculated as a percentage of the Image Pro total area. The percentage area of water, green and brown vegetation is shown in Table 5.6. The percentage data is plotted as the stacked bar charts shown in Figures 5.36 – 5.40. The use of percentage data offers an alternative way to analyse the performance of each pond in terms of vegetation with time.

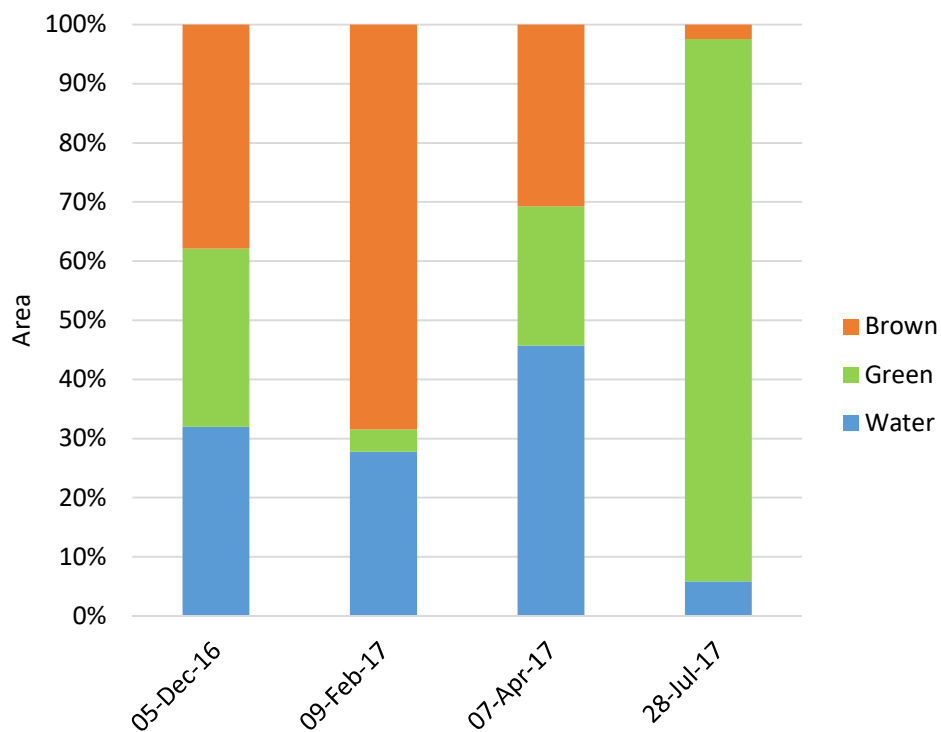


Figure 5.36 Percentage change in area of Pond 1 vegetation with time.

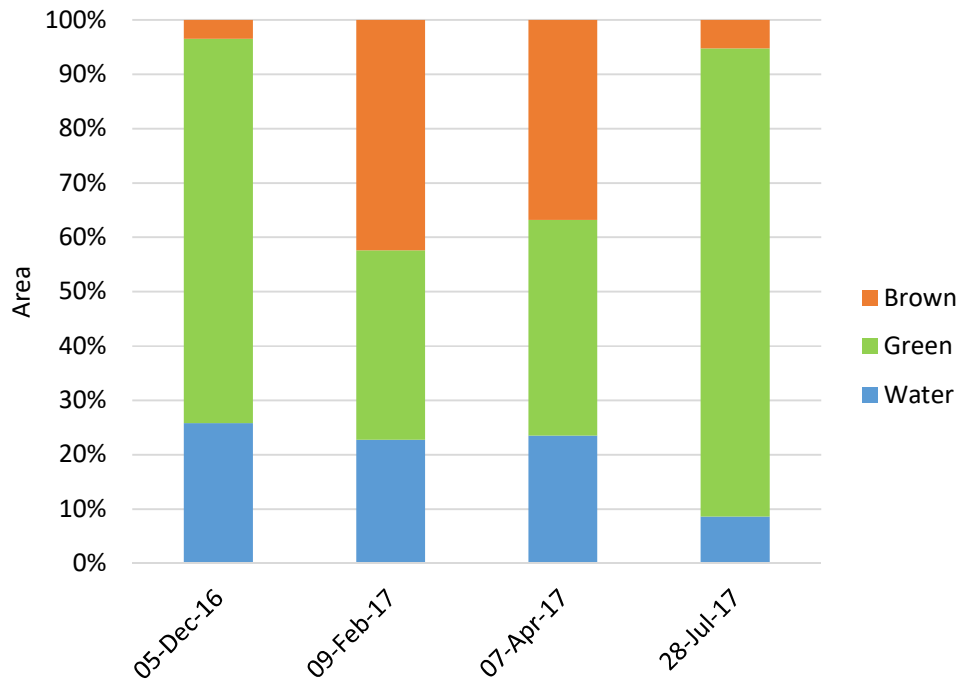


Figure 5.37 Percentage change in area of Pond 2 vegetation with time.

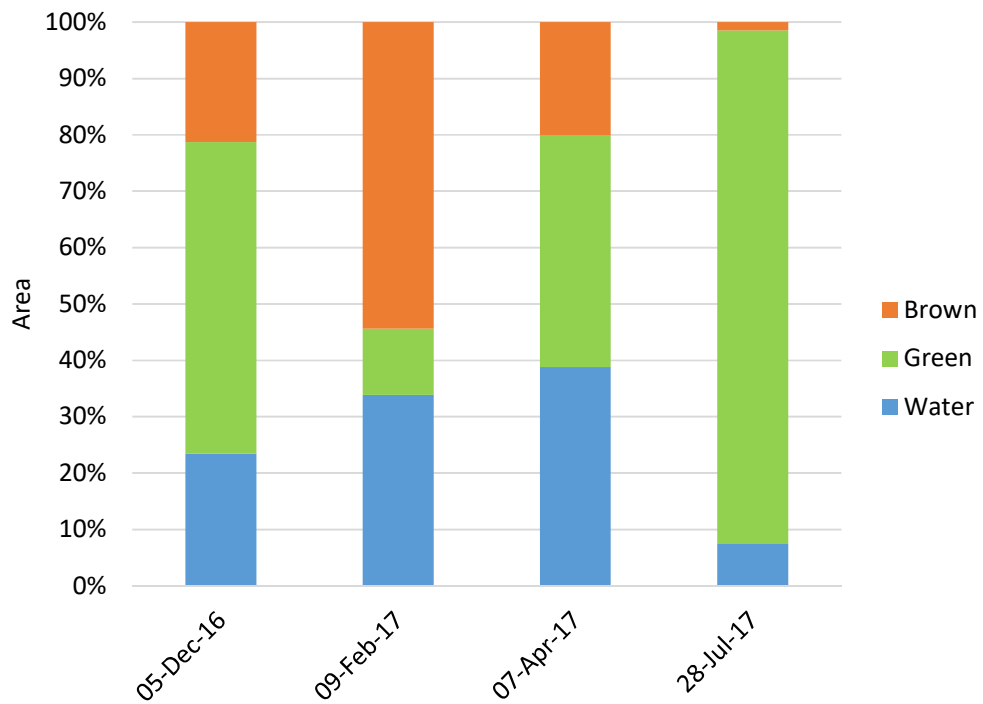


Figure 5.38 Percentage change in area of Pond 3 vegetation with time.

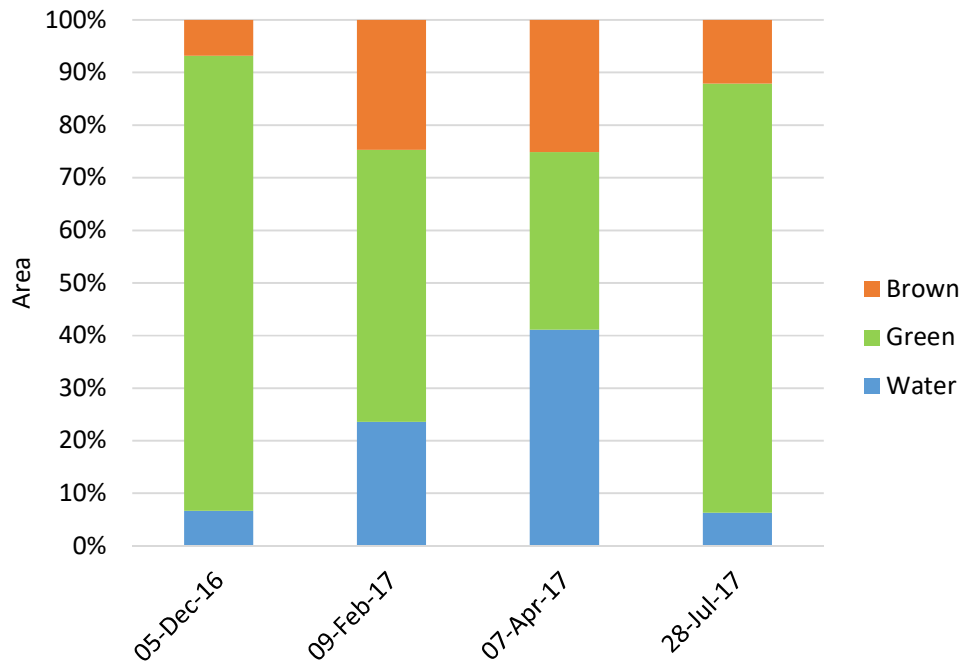


Figure 5.39 Percentage change in area of Pond 4 vegetation with time.

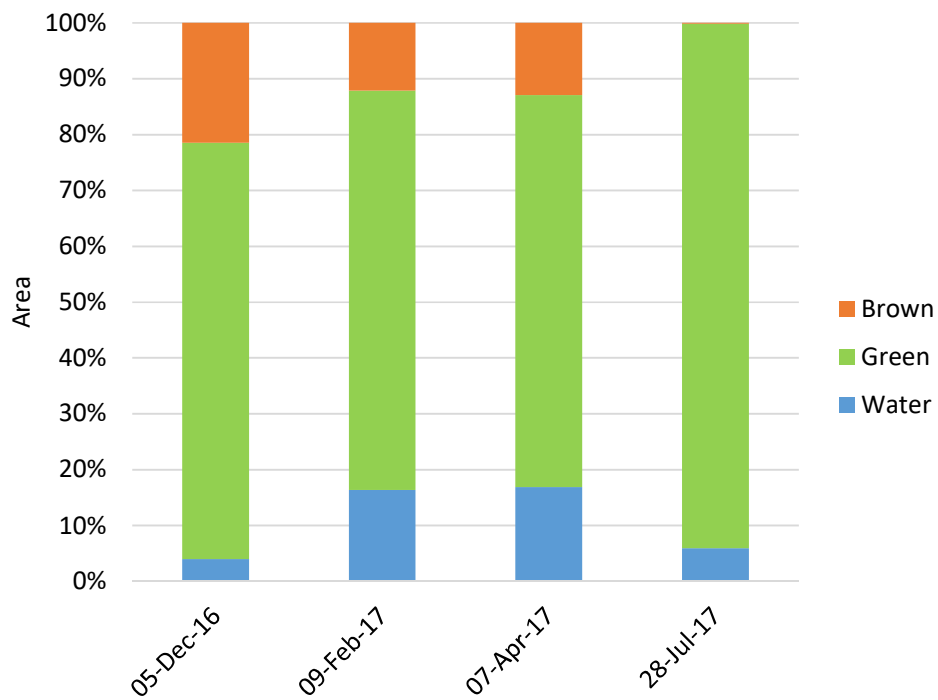


Figure 5.40 Percentage change in area of Pond 5 vegetation with time.

The change in Pond 1 vegetation is shown in Figure 5.36. In December 2016 32% of Pond 1 area was open water with no vegetation, 30% was healthy green vegetation and 38% was brown or decaying vegetation. By February 2017, the amount of open surface water had decreased to 28%. The amount of brown vegetation had increased to 68% leaving 4% green vegetation. In April 2017 the amount of decaying vegetation has decreased as the vegetation recovers. However, the amount of surface water was 45%.

This correlates with the die back of vegetation and disturbance of the pond as seen in Figures 5.26 and 5.36. By July 2017 there was a significant reduction in surface water to 6% with 92% being green vegetation. This shows Pond 1 vegetation to have recovered considerably over the 7 months. This change in Pond 1 vegetation correlates with the seasonal treatment performance results given in Chapter 5.3.3. This found BOD levels increase from 16.4mg/l in December to 259mg/l in April before improving to less than 6mg/l in July. Ammonia levels increased from 24mg/l in December to 36mg/l in February and improved to less than 5mg/l by July.

The change in Pond 2 vegetation is shown in Figure 5.37. This shows Pond 2 had much greater green vegetation in December 2016 than Pond 1 with almost 71% coverage. By February 2017 the amount of vegetation has remained but the distribution of brown vegetation has increased over 12 times to 42% coverage. By April the green vegetation (40%) begins to take over, reaching 86% by July with less 9% surface water.

Figure 5.38 illustrates that in December 2016, Pond 3 has less surface water than Pond 2 at 23%, although there is much more brown vegetation coverage at over 21%. By February 2017, the surface water has increased to almost 34% with much of the vegetative cover taken up by brown decaying matter at 54%. By April 2017 water area remains higher at almost 39%, however the brown vegetation has reduced, giving 41% green coverage. In July 2017 Pond 3 has approximately 91% green cover and only 7% surface water. Pond 3 vegetation distribution correlates with BOD performance discussed in Chapter 7 with 4mg/l measured in December, reaching 7mg/l by April 2017 before falling back to around 4mg/l by July 2017.

Figure 5.39 shows that Pond 4 has significantly lower surface water levels in December than the previous ponds at just under 7% and the vegetation is relatively healthy with over 86% green coverage. February 2017 shows signs of vegetation remaining healthy with only 25% of coverage representing brown or decaying matter. By April 2017 water levels reach the highest coverage of all ponds (41%), and with brown coverage remaining close to 25%, green coverage

has reduced to less than 34%. However, by July 2017 Pond 4 surface water reduces to 6% and brown coverage reduces to 12% allowing for over 81% green coverage. When related to the treatment performance discussed in Chapter 5.3, vegetation distribution again shows correlations with BOD levels with December reaching around 4mg/l and remaining at <3mg/l in February. By April 2017, BOD levels reach 5mg/l which correlates with the increase in surface water. Levels then return to around 4mg/l with an increase in vegetation in July 2017.

The change in Pond 5 vegetation is shown in Figure 5.40. This shows Pond 5 to have the mostly green vegetation that remained relatively unchanged over the 7 month period. This reflects the treatment performance of Pond 5 discussed in Chapter 7 which demonstrates the most stable levels of all contaminants between its inlet and outlet.

5.6.3 Drone Imagery and Wastewater Treatment Performance

Drone photographs can be used to quantify vegetation change with time and be correlated to wastewater treatment performance. They can quantify both vegetation growth and dieback highlighting areas of concern that may not be apparent from walking around each pond. For example, the problem with excessive free water in Pond 1 could be seen from the ground. However, Ponds 3 and 4 seemed relatively healthy from ground level with almost full vegetation coverage as seen in Figures 5.41 and 5.42 taken in March 2016. The drone photographs in Figure 5.26 – 5.30 showed Ponds 3 and 4 to have large areas of surface water from February to April in their central areas that could not be seen from the edges.



Figure 5.41 Pond 3 vegetation coverage from ground level in March 2016.



Figure 5.42 Pond 4 vegetation coverage from ground level in March 2016.

Drone images can also identify areas of open water, or preferential flow through the system. For example, the December 2017 and February 2017 images of Pond 1 shown in Figure 5.26 clearly show an area of surface water around the ponds edge. At ground level, this area of open water shows evidence of preferential flow as seen in Figures 5.43 and 5.44. Figure 5.45

confirms the presence of deep water around the edge when Pond 1 level was lowered for weir maintenance.



Figure 5.43 Pond 1 showing open water and suspected preferential flow.



Figure 5.44 Evidence of preferential flow along Pond 1 edge.



Figure 5.45 Deep water evident after draining Pond 1 for weir maintenance.

The drone images in Figure 5.26 also demonstrate how the area of surface water increases over time between December and April. This could be caused by the preferential flow deepening the pond bed around the edge through scouring, causing unfavourable conditions for plant growth.

Obtaining this drone based data allowed NIW to act accordingly to remediate the effects caused by such deeper areas of water. Pond 1 was drained in July so the concrete weir could be lowered by 500mm. This would allow the water level within Pond 1 to be reduced to less than 250mm as recommended within the design guide. The results of the remediation works are detailed further in Chapter 5.3. It was noted that after lowering the water level there was a substantial increase in vegetation coverage.

5.6.4 3D Modelling of ICW Pond Vegetation Growth

3D models were created using Zephyr Aerial with footage of the 5 ponds recorded on 3 site visits in December 2016, and February and April 2017. The method of deriving a 3D model from a drone video is summarised in Chapter 5. Scaling for each 3D model was obtained using

measurements of each pond taken with Topcon Total Station. An error margin of <2.5% was determined for each 3D model as shown in Table 5.7. The Booking Sheet distances measured with a Topcon Total Station are given to 2 decimal places as this method is known to be highly accurate. The Zephyr Aerial distances are given to 1 decimal place as their accuracy is thought to be lower due to consumer grade GPS.

The volume of vegetation within the 5 ICW ponds was calculated using the 3D models. Table 5.7 shows the volumes of each of the ponds taken from the 3D models of each of the 5 ponds of 3 site visits in December, February and April. The average vegetation volume per m² (m³/m²) were calculated using the average pond area from the Zephyr analysis and the vegetative area from Image Pro analysis. The difference between the vegetation (m³/m²) of the total pond area and vegetative area is also shown. Identifying the water surface of the pond is a critical issue to calculating a volume of vegetation growth. The data from Table 5.8 is plotted in Figure 5.46.

Table 5.7 Error of margin between Topcon Survey and Zephyr Aerial Distances.

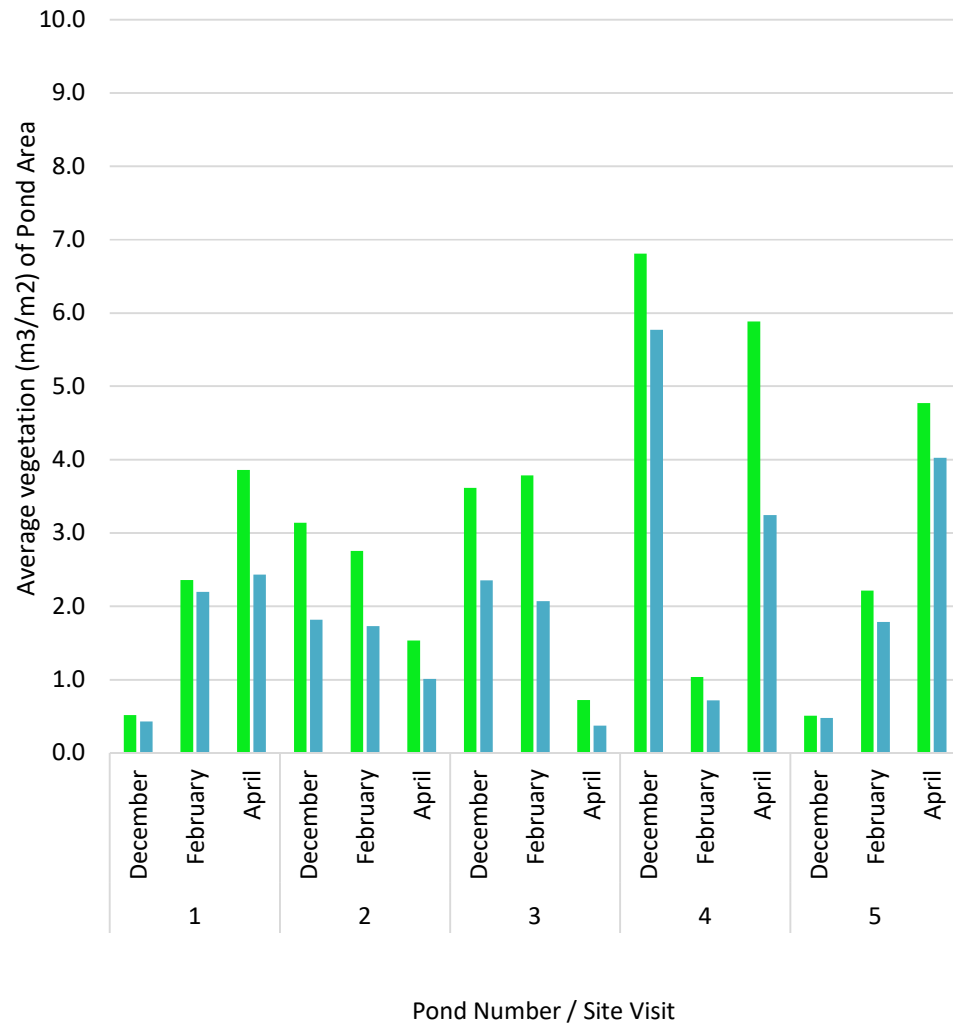
Pond Number	Booking Sheet Distances			Zephyr Aerial Distances			Error (%)	Average Error (%)
1	Control Point		Horizontal Distance	Control Point		Horizontal Distance		
	CB	MH	146.27	CB	MH	148.7	1.60	1.62
		T1	108.30		T1	106.5	1.63	
2	Control Point		Horizontal Distance	Control Point		Horizontal Distance		
	CB	MH	96.57	CB	MH	97.9	1.43	0.93
		Rock	97.16		Rock	96.8	0.42	
3	Control Point		Horizontal Distance	Control Point		Horizontal Distance		
	CB	MH	105.91	CB	MH	108.39	2.28	2.31
		T1	50.69		T1	49.51	2.34	
4	Control Point		Horizontal Distance	Control Point		Horizontal Distance		
	CB	MH	80.51	CB	MH	80.90	0.49	0.49
		Rock	78.68		T1	78.29	0.49	
5	Control Point		Horizontal Distance	Control Point		Horizontal Distance		
	CB	MH	57.77	CB	MH	57.91	0.24	0.24
		Rock	102.231		T1	101.987	0.24	

Vegetation data for each of the 5 ICW ponds on 3 site visits is plotted in a bar graph in Figure 5.46. This illustrates that Ponds 1 and 5 showed an increase in vegetation volume between December and April. Ponds 2 and 3 showed a decrease in vegetation volume between December and April. Pond 4 showed a large decrease in vegetation between December and February before increasing again by April.

Table 5.8 Pond Vegetation Volume and Plant Height using 3DF Zephyr Aerial Analysis.

Pond	Site Visit	Average Zephyr Total Pond Area (m ²)	Zephyr Volume (m ³)	Average Zephyr vegetation (m ³ /m ²)	Image Pro Vegetative Area (m ²)	Image Pro Vegetation (m ³ /m ²)	Difference (%)
1	December	5493	2350	0.4	4525	0.5	17.6
	February	5493	12073	2.2	5120	2.4	6.8
	April	5493	13367	2.4	3465	3.9	36.9
2	December	10576	19222	1.8	6122	3.1	42.1
	February	10576	18277	1.7	6638	2.8	37.2
	April	10576	10685	1.0	6974	1.5	34.1
3	December	9362	22067	2.4	6101	3.6	34.8
	February	9362	19370	2.1	5119	3.8	45.3
	April	9362	3453	0.4	4765	0.7	49.1
4	December	5973	34473	5.8	5060	6.8	15.3
	February	5973	4274	0.7	4122	1.0	31.0
	April	5973	19375	32.4	3293	5.9	44.9
5	December	6904	3289	0.5	6481	0.5	6.1
	February	6904	12317	17.8	5562	2.2	19.4
	April	6904	27794	40.3	5825	4.8	15.6

Figure 5.46 illustrates that the volume of vegetation within the total pond and the volume of the vegetation within the vegetative area follow similar trends across all ponds over time. However, there is a notable difference between the volume of vegetation when calculated across the area of the whole pond and the amount of vegetation when calculated across the area of identified vegetation within the pond.



■ Vegetation volume (m3/m2) of Vegetative area ■ Vegetation volume (m3/m2) of Pond area

Figure 5.46 Average vegetation per Total Pond area and Vegetative area.

This difference highlights the importance of factoring in surface water and areas of no vegetation within the ponds when calculating accurate vegetation volume over time. It is also recommended that surface water level is also factored in. If the surface level of open water is considered as the base level for calculating volume within the 3D models, a rise in water depth over time may cause the volume of vegetation to appear lower and give an inaccurate representation of the actual vegetation growth.

The data from Table 5.8 and Figure 6.46 can be correlated with the aerial images in Figures 5.26 – 5.30 and the data shown in Figures 5.31 – 5.35. Evidence shows that for Pond 1, as the area of vegetation decreased, the volume increased. For Pond 2, as the area increased, volume decreased. As the area of Pond 3 decreased, volume also decreased. Pond 4 showed little correlation between vegetative area and volume. Pond 5 showed an increase in volume with an increase in vegetative area.

The decrease in vegetation volume with an increase in vegetation area as seen in Pond 1 could be due to a rise in water levels within the ponds between December and April. This would cause the base level of volume calculation to be higher, causing the volume, and subsequent plant height, to appear lower. The opposite could be true for Pond 5 where vegetative volume increased with a decrease in vegetation area, i.e. vegetation density increased.

Thus, it is possible to measure the volume of plant growth for an ICW using aerial videography and creating a 3D model. However, this is an innovative method and further studies are recommended to improve the accuracy of calculations and monitor changes over time within the ponds.

Overall, the findings from this study demonstrate that drones can be used to collect high quality aerial data which can be used to create 3D models of each of the ICW ponds. The study also proved to be successful in calculating the surface area of the ponds using the modelling software, although further consideration is needed when calculating vegetation volume.

5.6.5 Use of Drone Photographs to Differentiate Plant Species

Pond 5 has both the greatest area and volume of vegetation. The planting plan for Pond 5 is shown in Figure 5.35. It shows the design to consist of areas or zones of single species and a mix of plants. Drone photographs were used to determine how each of the plant species became established with respect to its original planting and the flow of wastewater through the pond. The drone photograph of Pond 5 taken in July 2017 was analysed using Image Pro to determine whether it is possible to differentiate between plant species. Figure 5.47 shows Pond 5 from the edge. This shows how difficult it is to estimate vegetation coverage.



Figure 5.47 View of Pond 5 from the edge July 2017.



Figure 5.48 Pond 5 Aerial Image from July 2017 with ROI within the unhighlighted area.

The Pond 5 Region of Interest (ROI) is highlighted in Figure 5.48. Thresholding of the ROI identified 4 main classes of vegetation. These are shown in Figure 5.49 as differences in colour. Their distribution approximates the design planting plan. The area of each class was determined using the Count tool and presented as a percentage (Table 5.9). The total calculated area of each class is within 9% of the total vegetative area determined in the earlier drone photograph study. Using the planting plan and a walk around survey of Pond 5 each colour was denoted a dominant plant species. Figure 5.50 plots the percentage of each Class.

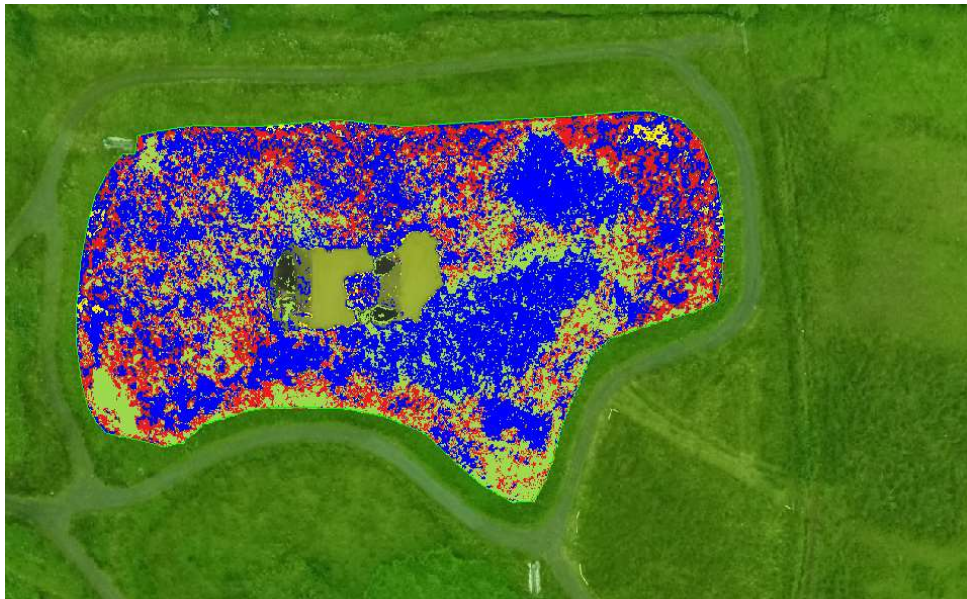


Figure 5.49 Species differentiation based on colour thresholding.

Table 5.9 Vegetation Area per Class Colour Threshold in Pond 5.

Class	Colour in photograph	Area (m ²)	Area (%)	Dominant plant species
Class 1	Green	3067	51	<i>Glyceria maxima</i>
Class 2	Dark green	1481	25	<i>Typha latifolia</i>
Class 3	Brown green	1324	22	<i>Carex riparia</i>
Class 4	Yellow green	123	2	Weed Grass
Total Area		5996		
Total Area of Vegetation from Image Pro Analysis		6579		
% Difference		8.87		

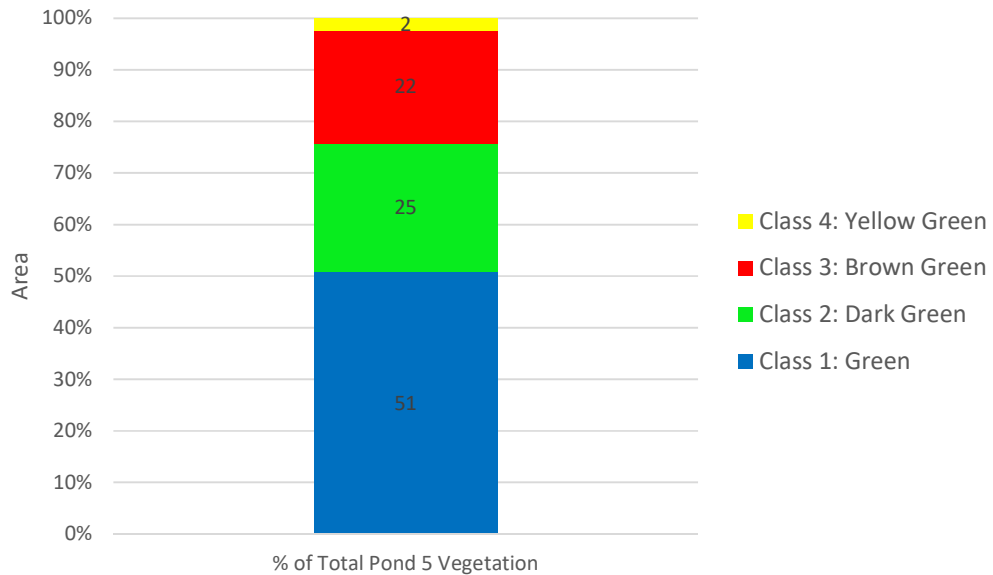


Figure 5.50 Pond 5 plant species in July 2017.

Comparison of the thresholded photograph with the Pond 5 planting plan shows the following:

- Class 1 with 51% of the total area is *Glyceria maxima*. Thresholding shows this plant to occupy two large blocks and to be established across the entirety of Pond 5.
- Class 2 with 25% of the total area is *Typha latifolia*.
- Class 3 seems to be well mixed across pond, particularly towards the discharge point to the left of the image
- Class 4 was identified as a weed grass during the walk around survey, explaining why it is confined to a small area within the pond.

This example demonstrates how drone photographs could be used to provide information not available from the edge of the pond. It illustrates how drones can be used to monitor plant and species performance within the ponds of an ICW. This information could be used to monitor the performance of the wetland in terms of maturity and establishment. It could also be linked to wastewater treatment performance. Further work is required over a longer period to better colour threshold each of the plant species over seasonal variations.

5.6.6 Drone Study Results Summary

This chapter has shown that drone photographs and video can be used to assess ICW vegetation changes with time. This can be expressed in terms of area to showing distribution of open water, green healthy vegetation and dieback. This offers new ways of assessing the vegetation of an ICW pond not possible from walking around its perimeter. It has been demonstrated that the photographs can be further analysed to determine the different plant species. The drone images show how issues such as deep water around the edges of Pond 1 have detrimentally impacted vegetation growth. The use of 3D modelling has been shown to offer a potential means of quantifying vegetation growth volume. These methods make it possible to better understand the relationships between plant species and the waste water treatment performance of the ICW ponds.

CHAPTER 6. DISCUSSION

6.1 Introduction

This chapter discusses the results of this research in relation to each of the research objectives described in Chapter 1. Each of the objectives are taken in turn so that the results can be discussed in terms of how they provide knowledge and understanding.

6.2 Objective 1: Critically review existing knowledge on constructed wetlands, and specifically the use of Integrated Constructed Wetlands for the treatment of domestic wastewater.

Chapter 2 developed an understanding of the performance of constructed wetland systems. The review of literature summarised key design differences between the types of constructed wetlands and their various applications (Table 2.3). This information allowed evaluation of each as a wastewater treatment method. Despite highlighting gaps in research and contradictory theories, the literature review enhanced understanding of the concept behind the performance and analysis of integrated constructed wetlands.

The literature review identified key differences between the common HSSF system and the newer ICW concept (Table 2.4). It highlighted that constructed wetlands can be successfully used for treating various types of contaminants (Figures 2.9 and 2.10). Chapter 2.10 of the literature review identified that key variables such as wetland design, hydraulic considerations, wetland location and local climatic conditions influence wastewater treatment performance of constructed wetlands in various ways, and to different levels of significance.

The literature review identified that the performance of constructed wetlands can be appraised on a number of factors other than their ability to treat wastewater. These additional factors were issues such as land use, odour, social impact, carbon footprint, economic value, operation and maintenance costs, and climate change mitigation potential. Figure 2.10 illustrates the influence of constructed wetland soil and plant composition between seasons on the storage of Nitrogen. Figure 2.11 emphasises the need to have a minimum of 4 ponds (or cells) when designing an ICW for wastewater treatment.

The literature review highlighted that all of these diverse factors are important for the appraisal of ICWs as holistic wastewater treatment systems. They should all be considered within the design of any future development. This is emphasised in Figure 2.12 which illustrates that the treatment of organic wastewater is reliant on various physical, biological and chemical processes which occur throughout the whole wetland system.

Chapter 2 reviewed current guidance documents on the use of Integrated Constructed Wetlands treating farmyard soiled and domestic wastewater in Northern Ireland. Differences in the treatment of these wastewaters can be seen in Table 2.7. This table highlights that a higher retention time is needed for adequate treatment of dairy wastewater than domestic wastewater, emphasising that the design principles should be more specific.

The review found the current ICW guidance to be outdated and inappropriate for the effective treatment of domestic wastewater in Northern Ireland. It identified the need to develop new guidance and emphasised the need for large-scale studies such as the Stoneyford ICW investigated in this research to provide necessary information.

The aim of the stakeholder engagement session was to determine the attitudes and opinions of key stakeholders on the key variables and appraisal contexts that influence the performance of an ICW in the treatment of wastewater. The results from the session are available in Chapter 5.2.

The stakeholder session proved to be valuable in relation to this objective. It highlighted significant gaps between research and industry practice as shown in the Pyramids of Significance. The findings emphasised the importance of stakeholder inclusion from an early stage for projects which aim to provide knowledge and understanding to industry.

It identified areas in which industry lacks knowledge and understanding and helped to identify key areas of significance for this research that were subsequently incorporated into this thesis. It was apparent from the stakeholder engagement session that there was insufficient experience within Northern Ireland on the use of ICWs for domestic wastewater treatment. The research carried out at Stoneyford ICW has helped to fill this knowledge gap.

6.3 Objective 2: Determine key variables for assessing Integrated Constructed Wetland performance.

A part of the literature review compared HSSF and ICW systems in their design, performance, and treatment capacities (Tables 2.3 and 2.4). This gave understanding of their wastewater treatment abilities so that developers such as NIW can make better informed decisions as to which may be more appropriate to meet their specific needs.

Key variables were identified to assess ICW performance including influent quality, amount and type of vegetation, amount and type of soil, ICW design (surface area, water depth, and number of ponds), hydraulic load rate and retention time, seasonal and weather changes, and the standard of effluent quality required.

The literature review took a systematic approach to these key variables and compiled a structured list of variables that impacts the treatment performance of constructed wetlands as shown in Figures 4.2 and 4.4.

There were key differences between the design of a constructed wetland when investigating performance for research purposes and the actual design that is implemented within the guidance used for constructed wetland development. For example, Table 2.4 shows that a surface area of 5-10m²/pe for a constructed wetland is successful in treating wastewater within the literature but 20-40m²/pe is implemented within the design guide.

The literature review found that the performance of constructed wetlands in their ability to treat wastewater is generally high. But there were many contradictions in the literature as to how well they performed under shock loadings (both concentration and flow of influent), seasonal variations, and wetland maturity (Table 2.5, Figures 2.8 and 2.9). These are major issues that could detrimentally impact the in-service performance of a full-scale ICW and need to be appreciated should they be used for the treatment of domestic waste.

The key variables found in the literature were used to form the basis of the stakeholder engagement session. This event confirmed that not all the key variables identified by the stakeholders had been identified within the literature. Additional variables such as operation and maintenance, ICW design planning were identified by stakeholders as important variables that would impact performance (Table 4.2).

This highlights the difference between academic perception and those responsible for designing, building and maintaining the built environment. The stakeholders weighted the key variables in order of significance as shown in the Pyramid of Significance in Figure 5.1. This gave understanding to how each of the key variables were perceived within industry.

It was found that the stakeholder weighting of key variables was different to that found in the literature. Whilst the stakeholder engagement session confirmed many of the key variables identified within the literature it also highlighted significant knowledge gaps between research and industry practice.

6.4 Objective 3: Review the design, construction and operation of a full-scale Integrated Constructed Wetland located at Stoneyford to assess its ability to treat domestic wastewater.

The Stoneyford Development summarised in Chapter 3 describes and explains the design and building of Stoneyford ICW and small-scale Test Rig. The chapter provides information from site selection, through the planning process to construction, commissioning, operation and maintenance of the working ICW.

The information summarised in Chapter 3 provides an insight of the many necessary steps and processes involved in constructed wetland development. It also identifies unexpected issues that may detrimentally impact any future ICW development. These issues include vandalism or construction delays due to animal disruption or poor weather.

Data for the full-scale Stoneyford ICW are represented in Chapter 5.3. These results illustrate the performance of the system in relation to water quality over its first few years. Figure 5.3 and 5.4 illustrate how the analysis of the four main contaminants i.e. Ammonia, COD, BOD and SS change within this relatively short period during which the ICW is developing its ability to treat wastewater.

The results allow comparison of water quality performance between ponds. The data indicates that the ponds performed differently against the various contaminants. Generally, water quality improved as it left each pond. However, analysis of the water leaving Ponds 1 and 2 was found to be most variable. In comparison there was relatively little variation in the analysis of water leaving Ponds 4 and 5. Pond 3 performed differently for each contaminant.

Figures 5.5 and 5.6 highlight that it is important to consider retention time when comparing the treatment of each pond and that the theoretical 90 day retention time is not always practical or true. Indeed, the issue of how long it takes wastewater to flow through the ICW network remains an important area that needs further work.

This area has been partially assessed by summing the data for each contaminant for each pond over the 19 month sampling period. Plotting this summed data allows area under the line graphs to be plotted. This gives a simplistic but clear representation of how water quality improves as it passes through each pond as shown in Figure 5.7.

This agrees with the findings from the literature in Figures 2.9 and 2.11 which finds water quality to improve with the number of ponds. This simple analysis suggests that a sixth pond at Stoneyford may have further improved water quality leaving the ICW.

Chapter 5.3 also related water quality data to seasonal variations to determine if there were differences in performance relating to changes in air temperature, precipitation, humidity and wind speed. Analysis found weak correlation between average weekly humidity and ammonia levels but as demonstrated in Table 5.3, the relationships between weather and contaminant levels show little to no statistical significance.

This is contradictory to the findings from literature (Mustafa, A., et al., (2009); Forbes, E. G. A., et al., (2011)). However, it agrees with the stakeholders' perception that although weather should be considered it is not a significant variable in ICW performance (Figure 5.1).

6.5 Objective 4: Design, build and monitor a small-scale research facility at Stoneyford.

The Stoneyford Development chapter describes and explains the development of a small-scale Test Rig. This was used as a research facility within the full-scale integrated constructed wetland system. Development of the test rig from site selection, design, construction, commissioning, operation and maintenance is summarised.

Information from the test rig was used to compliment data from the full-scale ICW to provide a better understanding of the impact of design on treatment performance. The results for the small-scale test rig given in Chapter 8 illustrate the performance of a constructed wetland in relation to water quality against the key design variables of surface area, water depth and wetland type.

Figures 5.19 – 5.22 illustrate that a difference in surface area between the Design Guidance rule of thumb of $20\text{m}^2 - 40\text{m}^2/\text{pe}$ has little impact on the wetland's ability to treat wastewater.

Although the larger surface areas were found to be more effective than the smaller surface areas, the impact on water quality performance was not significant.

This evidence could prove beneficial when scaled up to a full-scale system where the impact on wastewater treatment may be emphasised. The evidence presented in Chapter 5.5 agrees with the findings from Carty, A., et al., (2008) that ICWs should be designed with a surface area of between $20\text{m}^2 - 40\text{m}^2/\text{pe}$, but the results indicate that more emphasis should be placed on the benefits of the larger scale system.

With regard to water depth, Figure 5.23 illustrates that varying water depth between 50mm to 250mm had limited impact on the wetlands ability to treat wastewater. However, the shallower water depth of 50mm was more effective.

The test rig allowed investigation into the impacts of decreasing the water level of a HSSF from surface level 0mm to 200mm beneath the surface. Figure 5.24 demonstrates that changing the water level from 0mm to 200mm beneath the surface had little effect on BOD or ammonia treatment. However there was a significant correlation between water levels within the HSSF and the levels of suspended solids and COD. This result allows for the recommendation that keeping the water level as close to the surface as possible (0mm beneath the surface) would provide the most effective treatment of domestic wastewater in HSSF systems in Northern Ireland.

6.6 Objective 5: Offer advice to a revised guidance document for future Integrated Constructed Wetland provision for the treatment of domestic wastewater in Northern Ireland.

The literature review highlighted that ICW design has an influence on its performance in various ways. It is important that the appropriate constructed wetland design is selected for use in a specific location or for treating a specific wastewater source (Table 2.3). Appropriate selection will ensure that optimum performance can be achieved. Differences in constructed wetland design as shown in Table 2.4 highlighted the need for further investigations which were carried out in this research. Investigating such design parameters of both HSSF and ICW systems allowed for informed advice to be given on the appropriate options for treating domestic wastewater.

A review of the currently available guidance documents was carried out to evaluate their suitability for the implementation of ICWs for the treatment of domestic wastewater in Northern Ireland. It was concluded that the information and research within the most appropriate document for Northern Ireland was outdated.

There was the need for better guidance as the use of a combined guidance document for both agricultural and domestic waste was inefficient and unsuitable for a natural system that is not only site specific, but also specific to each individual application.

Chapter 3 summarised the steps involved in the construction of Stoneyford ICW planning through to commissioning. It includes issues that impacted the works such as poor weather conditions, disrupted screening, late planting and plant disruption.

Additional issues during the first few years at a functioning ICW also need to be appreciated. For example, an unexpectedly dry winter and spring during the sampling period between 2016 and 2017 influenced water levels with some starting to dry out (Figure 5.11). This meant that wastewater started to take preferential flow through the areas of deeper water and was not being treated adequately by the processes within the plants and soil structure.

This type of additional information learned from the Stoneyford ICW is not considered in the current guidance and as a result, NIW were not aware of the potential measures to mitigate impacts. Future guidance needs to take into consideration the different issues that occurred at Stoneyford as they have the potential to detrimentally impact performance of the ICW. This will advise future ICW developers on suitable mitigation approaches.

Another unexpected issue was that of wildlife suspected of disrupting pond beds and increasing suspended solid and ammonia levels in ponds 4 and 5 as described in Chapter 5.6. This was unexpected as the holistic design approach of Stoneyford ICW was to actively encourage wildlife in Pond 5 with the construction of an island surrounded by deeper water in which the plants would not grow. There was evidence of birds in the open water areas that developed in Pond 1 suggesting that such areas of open water do encourage wildlife to the site.

Chapter 5 suggests that bird-life should be discouraged from the Ponds of an ICW as they are suspected of detrimentally impacting the wastewater treatment process. Design features of islands and open water in these ponds are not recommended as they need to be fully vegetated for optimum treatment.

Based on Stoneyford it is expected that these issues are likely to occur in any future developments and should be reconsidered within a revised guidance document. It is suggested that additional non-treatment ponds and wildlife features are implemented within the landscaping of an ICW site and kept separate from the treatment works.

Chapter 5 highlights structural issues that should be considered within a new guidance document. Very important is the evenness of the pond floor. Pond 1 developed areas of open water and during the dry winter it was apparent that the water depth was not uniform. A survey of the Pond 1 floor identified areas of deeper water corresponding to open water.

As water depth is critical to plant growth this direct evidence illustrates the need for close controls when constructing what may be considered a natural landscape in contrast to hard engineering practices such as concrete or artificial linings. Site investigation prior to construction needs to consider the historical use of the land. For example, the water course that was found to cut through the location of Pond 1.

The water quality data for the full-scale system highlights that treatment within the ICW could be cyclical during its earlier years and take time to stabilise and reach equilibrium (Figures 5.3 – 5.6). The investigations reported in this thesis only account for the early life of the ICW. Research needs to continue to determine how Stoneyford ICW continues to mature and reaches equilibrium.

This probably requires an additional 3 to 5 year study to better understand whether early life cyclic events continue or if the ICW becomes stable. Based on the evidence in Chapter 5.3, a period of at least one year is recommended from the completion of the ICW development to the commencement of wastewater treatment to allow for the system to establish and settle.

Data from the small-scale test rig found each test bed performed differently in the removal of contaminants. T1-T3 performed better for BOD, suspended solids, and ammonia removal while T4 and T5 performed better for COD (Figure 5.18). Results highlighted that a change in surface area between 40m² – 80m² had little impact on the wetlands ability to treat wastewater although the larger surface areas did tend to be more effective. Based on the evidence provided in Figure 5.19 – 5.22, a larger area is more effective. Depending on the influent concentration and loading a smaller area can also be effective.

Results from both the full scale and small scale systems emphasise that current design parameters could be made more concise, with the importance of having a larger surface area and shallower water depth being more appropriately explained.

With respect to this objective, the research presented in this thesis not only highlights discrepancies or inaccuracies within the current guidance, but also identifies new issues which are likely to reoccur in future ICW developments. This needs to be included in the guidance when revised.

6.7 Objective 6: Investigate the use of drones as a method of monitoring plant performance and identify links to wastewater treatment performance.

Chapter 5.6 considered how drones can be used to monitor ICW plant performance. The chapter considered data over a 7 month period from winter to summer. It was possible to do a complete drone study of Stoneyford in approximately 30 minutes. This study clearly found that drones can provide a new data-set that can help explain the relationship between plant performance and overall performance of the ICW. It was able to identify and quantify factors not possible by walking around each pond.

Photographic and video images can be used as the basis of 2D and 3D investigations as shown in Figures 5.26 – 5.30 and Figures 4.17 – 4.21. Figures 5.36 – 5.40 illustrate how the amount of surface water, healthy vegetation and level of die back changed during the 7 month study period. Analysis of these images was able to quantify the amount of each condition as shown in Tables 5.4 and 5.5. Figure 5.46 shows the potential for calculating the volume of vegetation using 3D modelling software

Figures 5.49 and 5.50 demonstrate how drone images can be used to monitor differences between species distributions within the wetland. This data can be correlated to wastewater treatment performance.

This new type of information can be used as a method of monitoring the performance of the ICW ponds over time in terms of vegetation growth and die back, and species population. This new data set is not available at ground level and will provide developers such as NIW with a means of highlighting problems such as open water described in Chapter 5 and allow prompt remedial action to be taken.

6.8 Overall Discussion of Results

The results of the studies described in Chapter 5 have allowed the aims and objectives of this research to be achieved. The main findings and observations from these studies are now discussed:

The stakeholder engagement identified limitations with available literature, including a lack of consideration for planning and development regulations as well as health and safety concerns of the local community. Throughout the literature review, much of the available literature focused on the performance of constructed wetlands and their ability to treat wastewater. ICWs however are designed and promoted on their holistic sustainable concept which is inclusive of social, economic and environmental considerations. However, it is noted that there were no community representatives present to provide their views.

It would be beneficial for future developments to include all key stakeholders, including planners, designers, regulators, engineers, ecologists and community representatives, throughout the planning and design process so that a more holistic approach to ICW development can be obtained. This would allow for the development of a system that communities can feel they have contributed to, and may prevent issues caused by vandalism, poor plant development, flooding and clogging described in Chapters 3 and 5.

The full-scale ICW system at Stoneyford demonstrated evidence to suggest that Ammonia and COD performances are impacted over time, confirming the results of studies conducted by Mustafa, A., et al., (2009). The results also suggested that BOD and SS were not impacted over time which is contradictory to findings by Kayranli, B., et al., (2009).

Results from the full-scale ICW also provided evidence which suggests that performance of ponds 3, 4 and 5 in treating Ammonia may be cyclical with reduced performance occurring at similar times each year (winter period). This confirms previous studies by Mustafa, A., et al., (2009) who found poorer ammonia removal in winter months at a similar ICW in the Annesvalley Catchment in Ireland. However, when the water quality results were analysed against weather conditions in Table XX, no statistical significance was identified. By using a drone to monitor and measure plant performance as described in Chapter 5, the observation could be made that plant growth and density is poorer during winter months. This provides sufficient evidence to suggest that the treatment of ammonia within a constructed wetland is attributed to by the plants performance.

Results from the Test Rig indicated that a change in water depth between 50mm – 250mm had little impact on the wetlands ability to treat wastewater. It was noted however that the shallower water depth of 50mm did tend to be more effective than the deeper ponds but that differences were marginal. Observations from Pond 1 within the ICW also allowed for a better understanding of how water depth in the pond can have an impact on wastewater treatment. As described in Chapter 5.4 the water depth in Pond 1 became uneven, causing areas of open water where plants were unable to grow. Once the pond was drained and the water levels lowered to a suitable depth of less than 250mm, the vegetation flourished and open areas of water were covered.

As noted above, the plants have an impact on how effective the wetland is in treating wastewater and thus, it can be concluded that an increase in water depth could potentially have a negative impact on ICW treatment performance. This confirm research with Cui, L., et al., (2012) who found that a greater water depth had a negative impact on plant growth. The evidence from the results would also suggest that on a larger scale, the differences in wastewater treatment between water depths of 50mm – 250mm within the test rig would be emphasised.

A significant finding from this research has been the successful application of a drone to measure and monitor plant performance within an ICW. This method makes it possible to better understand the relationships between plants and the wastewater treatment performance of the ICW ponds as identified through the results and observations of the full-scale ICW and test rig.

CHAPTER 7. CONCLUSION

7.1 Introduction

The aim of this research was to improve understanding of Stoneyford ICW early life performance for the treatment of domestic wastewater in Northern Ireland. This chapter provides the conclusions to the research by highlighting the key findings of the research.

7.2 Significant variables that impact the treatment performance of an ICW for domestic wastewater

This research has considered the early life performance of a full-scale ICW for the treatment of domestic wastewater. Review of the relevant literature, stakeholder engagement and analysis of data during this early life period has found that there are a wide number of significant variables. The variables identified include water depth, soil characteristics and depth, pond geometry, hydraulic retention time, hydraulic loading rate, climate, plants, planning, operation and maintenance. An ICW by nature is a holistic concept, reliant on these identified factors ranging from design, through to daily operation. The Stoneyford ICW has identified how all these factors need to be considered in this holistic framework. Although the impacts of the factors of water depth and plants have been highlighted throughout the discussion of this research, it is concluded that all variables need to be considered to ensure successful operation of the ICW.

7.3 The design of an ICW can be improved to optimise the performance of domestic wastewater treatment

There is limited experience with the use of ICWs for the treatment of domestic wastewater with most of the design principles based on the treatment of agricultural wastes. Stoneyford is the first full-scale ICW for the treatment of domestic wastewater in Northern Ireland. It has allowed observations and provided data which will optimise the design and decision making process for future ICW installations. The following conclusions should be utilised to improve the design of future ICWs in Northern Ireland;

- Wetland ponds are currently designed to a minimum of 20m² pe with a water depth of less than 250mm. Evidence from Stoneyford ICW suggests that ICW performance is more effective when surface area is increased to 40m² pe with a water depth of not less than 50mm.
- Planting of young wetland species should be carried out early in the planting season to allow for adequate growing and establishment;
- Influent flow into the wetland should be withheld until the wetland is in a state of full plant growth to prevent the drowning or overburdening of young or weak species;
- Disturbances to the ponds once planted should be kept to a minimum. If disturbances are necessary, it is recommended that works are carried out during autumn and winter months to minimise impact on plant species;
- Care should be taken during initial construction and during any subsequent works to ensure the water depth of the pond remains constant;
- Care should be taken to ensure the beds of the ponds are compacted to avoid later differential settlement that may cause areas of deeper water;
- Influent flow into Pond 1 should be kept reasonably constant to reduce the effects of surges on ICW performance;
- An additional source of influent should be considered during periods of dry weather, so as to reduce the complications of clogging. Potential sources could include local stream water, clean water or recycling of discharge from the system.

7.4 Relationship between plants and wastewater treatment

Plant performance changed significantly over the test period with significant die back demonstrated during the winter months. Treatment performance was reduced during winter months, especially with regards to ammonia treatment. Correlating treatment performance with weather data found that changes in weather had little significant impact on wastewater treatment within the ICW.

It is concluded that wastewater treatment performance is dependent on plant performance. Evidence suggests higher vegetation density will allow for improved treatment performance. Conditions that are unfavourable for sustaining vegetation growth that create areas of open

water are to be avoided as they allow the wastewater to flow through the pond and not be fully treated.

7.5 Effect on ICW by environmental, ecological and seasonal factors

Evidence suggests that the ICW at Stoneyford was affected by environmental, ecological and seasonal factors. For example, dry periods caused wastewater to flow through areas of deeper water as opposed to the plant and soil structure. Wildlife and animals are suspected of causing disturbances to plants and sediments. The plant species were impacted by seasonal factors, showing substantial die back during winter months and significant regrowth over summer months.

However, there was little evidence to suggest that the ability of the ICW to treat wastewater was significantly affected by these environmental, ecological and seasonal factors. There was no significant correlation between water quality and weather changes. Instead, wastewater treatment was suggested to be cyclical or impacted by plant establishment and maturity within the ponds.

7.6 Performance of plant growth can be better monitored using a drone

The performance of plant growth and its distribution can be better monitored using drones and analysis of captured imagery. Using aerial imagery allows for an accurate analysis of plant growth, density and species monitoring within each of the ponds. This is of particular benefit to those wishing to use plant performance as a method of predicting wastewater treatment capacity and/or proactively identify early issues that may reduce overall wetland performance.

7.7 Ammonia removal can be directly related to plant performance within an ICW

Ammonia removal was poor during the winter months between October and February, but results indicated that this was not directly related to weather conditions. Plant performance was also poor in winter months as demonstrated through analysis from the drone study. Thus

ammonia removal can be directly linked to the poor performance of the plants as a result of climatic and seasonal changes, but not directly related to weather.

7.8 ICWs a viable alternative to traditional wastewater treatment works in treating domestic sewage in Northern Ireland

ICWs are a viable alternative to traditional wastewater treatment works in treating domestic sewage in Northern Ireland. Stoneyford ICW has been shown to successfully treat domestic wastewater during its early years. Evidence suggests that performance will improve as the wetland continues to mature. Use of Stoneyford ICW as a full-scale trial has brought substantial benefits to the wastewater treatment industry in terms of knowledge and understanding, providing an excellent example from which to learn and improve future developments.

CHAPTER 8. RECOMMENDATIONS FOR FUTURE WORK

8.1 Introduction

This research investigated the early life performance of Stoneyford Integrated Constructed Wetland for the treatment of domestic wastewater. The findings within this thesis have highlighted the need for further research in the following areas:

- The need to continue monitoring Stoneyford ICW to better understand how it matures as a means of treating domestic wastewater;
- A Delphi study of stakeholders from the whole of the UK and Ireland;
- Develop the findings of the small-scale test rig into larger scale systems to improve understanding of key design parameters;
- Continue developing the use of drones to monitor and quantify plant performance. Particular emphasis should be placed on:
 - Improving estimation of plant growth using 3D modelling;
 - Correlate plant performance with wastewater treatment performance;
 - Develop a catalogue of signatures for image analysis of individual wetland species across seasonal variations.
- Develop the observation of the impact of wildlife on ICW treatment performance through ecology and biodiversity surveys and determine a correlation between wildlife activity and water quality;
- The findings of this research should be used to improve guidance relating to the use of integrated constructed wetlands for the treatment of domestic wastewater in Northern Ireland.

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APPENDICES

APPENDIX A: STAKEHOLDER ENGAGEMENT FEEDBACK BOOK



School of Built Environment



Integrated Constructed Wetlands: Stakeholder Engagement Feedback Book

Name	
Job Title	
Employer	
Discipline	

Contents

Stakeholder Engagement Brief: Integrated Constructed Wetlands

Presentation Notes

Research Findings

Discussion Points

1. Knowledge of ICWs and their relevance to policy frameworks and sustainable development strategies;
2. Identification and weighting of significant variables for overall performance;
3. Identification and weighting of key performance criteria for overall ICW appraisal;
4. The future of ICW installations;
5. Best Practice Guidance Document.

General Comments

Contact Details

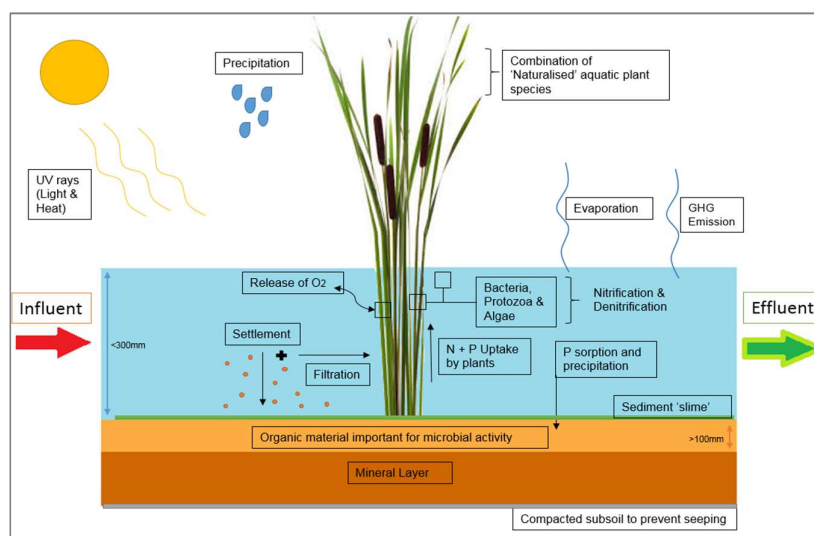
Stakeholder Engagement Brief: Integrated Constructed Wetlands

Introduction

Clean water is crucial for our survival, and as human populations continue to grow, it is becoming increasingly apparent that the protection of limited water resources is critical. As such, there are a number of regulations in place with regard to water protection, with the European Water Framework Directive 2000/60/EC (WFD) being the most integrated. The promotion of sustainability has been included within the WFD, and as such, water protection is also integrated into EU sustainable development strategies. Thus, legislative requirements coupled with global pressures to develop sustainably have created an industry which combines environmental protection with innovative engineering techniques, allowing developers and businesses to work responsibly whilst complying with legislative requirements. Consequently, although there are now numerous engineering techniques available to remediate and prevent water pollution, the use of Constructed Wetlands is a method which is proving to be a potentially viable and naturally available solution.

Constructed Wetlands

Constructed Wetlands are engineered systems designed to simulate the bio-filtration processes of a natural system in order to remediate contaminated wastewater and mitigate the pollution of nearby water bodies. This is done by using a number of strategically chosen aquatic plants, suited to the specific site, which filter and remove contaminants from the water as it flows down the gradient of the land. Constructed wetlands are designed to work as an integrated ecosystem, combining the functions of the natural environment with human activities, to help enhance overall water quality i.e. they are a natural means of treating wastewater, but through a controlled and manageable method. The constructed wetland principle has been applied to the treatment of a range of influents from sources such as dairy farming, abattoirs, industrial effluents, domestic sewage, combined sewage and stormwater flows. As the polluting influent flows through the ponds, it is subjected to a number of integrated processes such as sedimentation, filtration, nitrification, denitrification, and sorption and plant uptake until it exits the pond system into a nearby watercourse as seen in the diagram below.



Constructed wetlands can take various forms depending on their application and can be free flowing (FWS) or have water flow beneath the surface, either horizontally (HSSF) or vertically (VSSF). Some systems employ a hybrid approach which uses a combination of the different designs to try to improve efficiency. Another type of constructed wetland is an Integrated Constructed Wetland (ICW) which is a more recent variation of previous designs. A summary of the different wetland types and their key designs features can be seen in the table below.

Summary Table of Constructed Wetland Design

Variables	FWS	HSSF	VSSF	Hybrid	ICW
Soil Depth	>15mm	>300mm	>500mm	Various	150mm
Water Depth	>285mm	<200mm	<250mm	<300mm	<300mm
Plant Type	Emergent and/or Floating	Emergent	Emergent	Various	Emergent
Surface Area	20-40m ² /pe	5-10m ² /pe	1-3m ² /pe	3-10m ² /pe	20-40m ² /pe
No. Ponds	1+	2-5	2-5	Various	>4
Application	Tertiary treatment of stormwater and municipal wastewater	Municipal, domestic, industrial, food-processing, agriculture, landfill.	Landfill, domestic, municipal.	Municipal, domestic, industrial, food-processing, agriculture, landfill	Municipal, domestic, industrial, food-processing, agriculture, landfill

ICWs are a relatively new addition to the constructed wetland concept and their design is based on the concept of FWS wetlands, in that the water flows freely above the surface of the soil. However, ICWs differ from FWS wetlands in that they are an integrated method to managing the natural resources of land and water. ICWs use a holistic approach to integrating the concept of constructed wetlands into the local landscape, soils, topography, and biodiversity, to create a sustainable and viable wastewater treatment system which mimics the processes and developments of a natural wetland. Over the last 40 years, research on constructed wetlands for various types of wastewater treatments has expanded and enhanced understanding of the processes and interactions involved. Despite this, there still remains a number of unknowns, providing great prospect for further research which will develop a better appreciation of the concept of constructed wetlands and their potential as sustainable alternatives to traditional wastewater treatment works.

Northern Ireland Water has recently implemented the first ICW in the UK for the treatment of domestic and municipal waste at Stoneyford. It is hoped that this wetland proves to be an effective and sustainable alternative to traditional wastewater treatment works for NIW and subsequently, they have invested considerable amounts in providing substantial apparatus for the collection, measurement and monitoring of treatment performance. Overall, it is foreseen that an evaluation can be made on ICWs for the treatment of domestic waste, so that they can be appraised in the context of political frameworks and sustainable development objectives. It is envisaged that this will then support the development of a 'Best Practice' guide to assist in the decision making process for industries wishing to implement constructed wetlands for the treatment of wastewater.

Research Project

This research project is supported through the Department of Employment and Learning (DEL) Co-operative Awards in Science & Technology (CAST) scheme; the industrial partner is effectively NI Water, with direct involvement from White Young Green (Consulting Engineers). The overall aim of this project is as follows:

'To Develop a Deeper Understanding of the Performance and Analysis of Integrated Constructed Wetlands for the Treatment of Domestic Wastewater.'

In order to do have an adequate understanding of ICW performance, we need to identify the key variables that influence this performance. Thus, we will compile a list of variables and performance criteria as identified by using a combination of literature review, previous case studies and the opinions of key professionals from various industries. From this, we can then appraise the information and develop a more precise list of key variables of which we can focus our attention, in order to develop a more efficient design methodology for future ICW implementation.

Aim of the Stakeholder Engagement Session

The aim of the stakeholder engagement¹ session is to gain knowledge and understanding of the attitudes and opinions of key stakeholders on the factors that influence ICW performance so that the significant variables for optimum ICW performance can be determined. Findings from the stakeholder engagement session will be used to inform the ICW Performance assessment and aid the development of an ICW 'Best Practice' Design Guide for use by key stakeholders.

Objectives

In order to satisfy the aims of the stakeholder engagement sessions, the following objectives need to be achieved:

- Develop an understanding of the attitudes and opinions of key stakeholders on ICWs as an alternative to traditional wastewater treatment works;
- Identify how the use of ICWs as a wastewater treatment method is perceived by stakeholders from various backgrounds;
- Develop a perception of how stakeholders relate ICWs to current EU policy frameworks and sustainable development objectives;
- Identify key variables that impact on ICW performance and establish a weighting of significance so that a more focused approach can be taken towards research;
- Identify key appraisal contexts of ICW installations and establish a weighting of significance;
- Develop an understanding of how stakeholders envisage future ICW application;
- Gain an understanding of stakeholder attitudes towards an 'ICW Best Practice' Guidance Document, including their views on the requirements within particular industries/applications, the format of the document, key points to include and accessibility.

Process of the Stakeholder Engagement Session

It is envisaged that these objectives will be met through a structured discussion² with the stakeholders involving a series of questions; this will be facilitated by a Chairman after the delivery of a short presentation on ICWs, their processes, performance variables and literature findings. The key questions or discussion points for stakeholders will be:

- Knowledge of ICWs and their relevance to and context within Policy Frameworks and Sustainable Development Objectives;
- Identification of the listed variables which are deemed to be significant to influencing overall ICW performance;

- Weighting of the listed variables in order of significance to influencing performance;
- Weighting of the listed variables in order of priority for further study;
- Opinions on the future of ICWs in terms of implementation and additional/alternative applications;
- Opinions and comments for an ICW 'Best Practice' Design Guide to develop an applied document applicable to various industries and applications.

After the structured discussion around these key points, the Chair will seek broadening of the discussions so that a more detailed and interactive understanding of opinions and attitudes is developed.

The entire session will be audio recorded so that a transcript can be written up; also, stakeholders will be asked to record written answers and comments on a provided pro-forma. These will be collected at the end of the session and each stakeholder will subsequently receive a copy of the summarised notes and findings of the session.

Recording of Results

During the session an audio recording will take place and stakeholders will be asked to record their own comments in writing throughout. This information will then be used as a source of data which will then be analysed and interpreted.

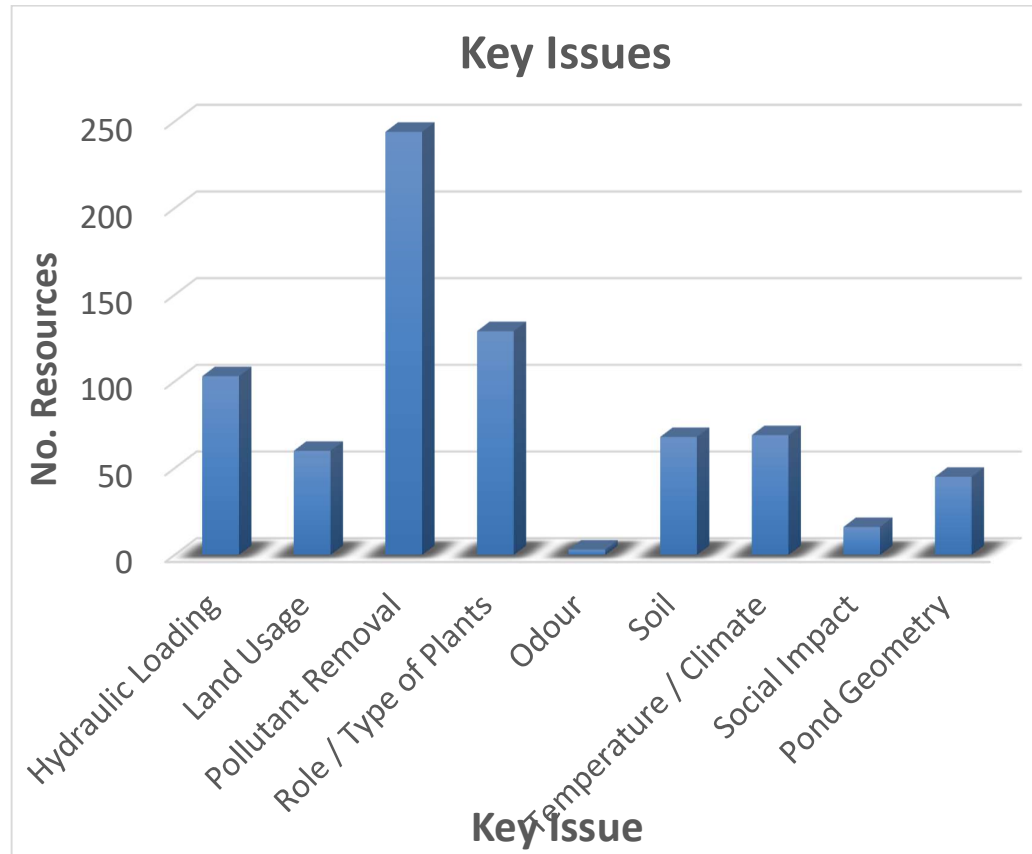
Summary and Feedback

Results from the session will be written up in the form of a report and distributed to each of the stakeholders for further comments or clarification. Any comments written on the stakeholders' notes sheets will remain anonymous. Once this is completed, final results will be compiled and included within the research thesis.

1. **Stakeholder engagement** is the process by which an organisation involves people who may be affected by the decisions it makes or can influence the implementation of its decisions. They may support or oppose the decisions, be influential in the organization or within the community in which it operates, hold relevant official positions or be affected in the long term. (Wikipedia, 2015)
2. In a **structured discussion**, each participant has a chance to voice her comments about the various options. This might include what she sees as the option's strengths and weaknesses, likely impacts, or major concerns. One person talks at a time and it is everyone else's job to listen carefully. (Tom La Force, 2013)

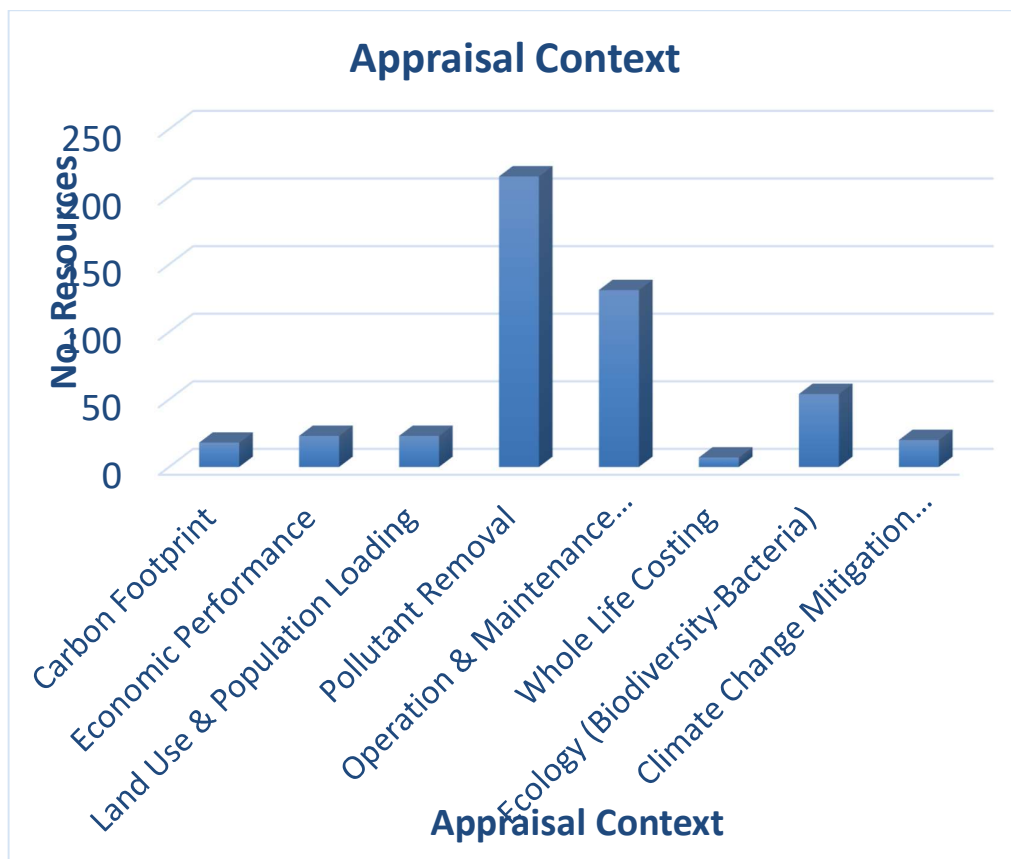
Research Findings

Key Issues Chart

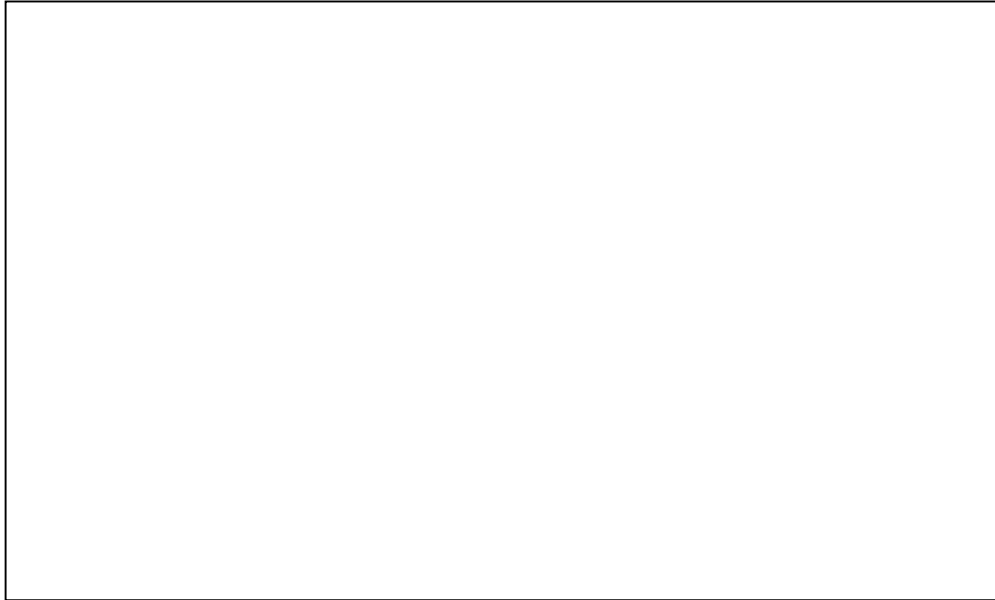


Comments:

Appraisal Context Chart



Comments:



Discussion Points:

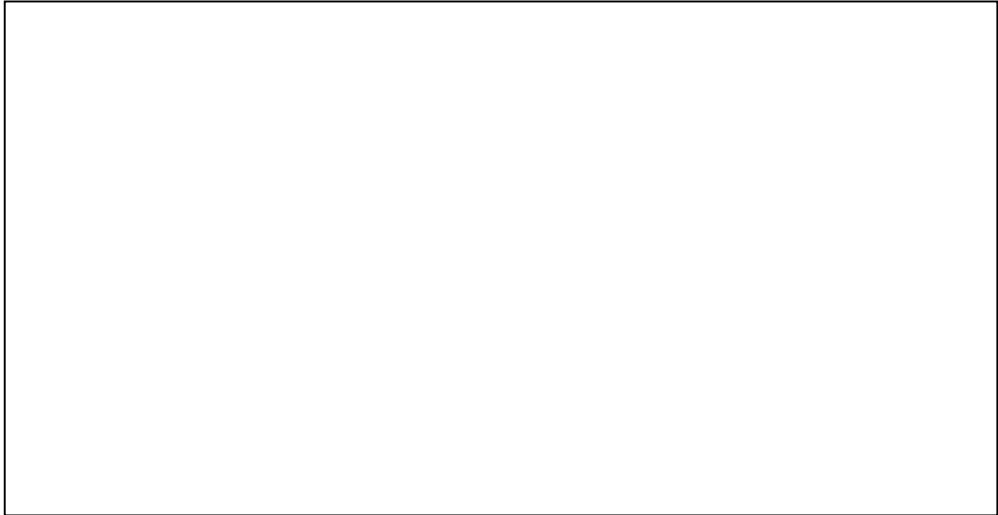
Please record your comments on each of the discussion points in the space provided.

- 1) Please detail your current knowledge of ICWs, including their relevance to and context within Policy Frameworks and Sustainable Development Objectives;



- 2) Key Variables:

- a) Based on your previous knowledge and today's presentation can you identify the key variables which impact overall ICW performance;



- b) Can you now weight the agreed variables in order of significance to influencing performance using the pyramid below;

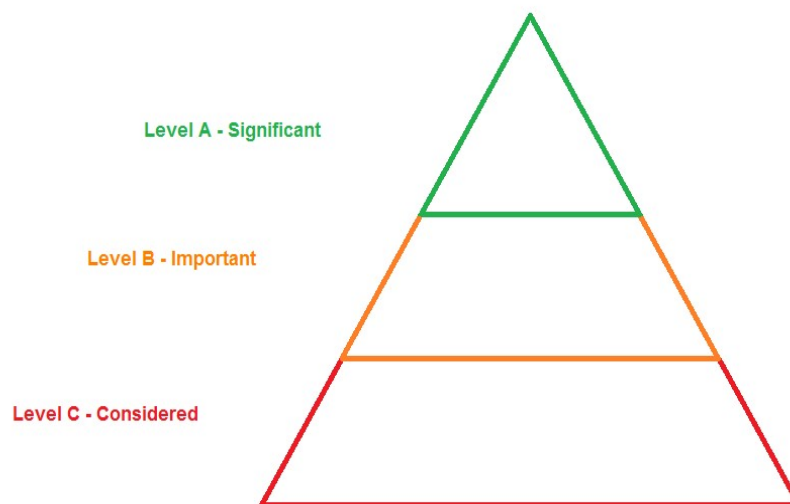
You can divide the pyramid into further sections to represent level of significance within each of the 3 levels.

Definitions:

Significant = Has, or is likely to have a **major effect** on ICW performance;

Important = Has, or is likely to have a **strong influence** on ICW performance;

Considered = Does not have significant effect or strong influence but must still be **considered as contributing** to overall ICW performance.



3) Performance Criteria;

- a) Based on your previous knowledge and today's presentation can you identify the key performance criteria for overall ICW appraisal;

Comments:

- b) Can you now weight the agreed criteria in order of significance to overall ICW performance appraisal;

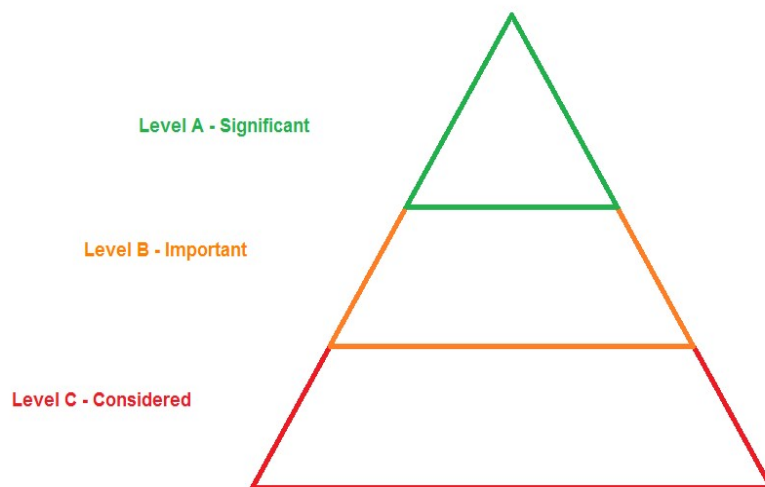
You can divide the pyramid into further sections to represent level of significance within each of the 3 levels.

Definitions:

Significant = Is **critical** to the overall appraisal of ICW performance;

Important = Is of **notable consideration** in the overall appraisal of ICW performance;

Considered = Does not require significant or important attention when appraising overall ICW performance but must still be **considered**.



- 4) What is your opinion on the future of ICWs in terms of implementation and additional/alternative applications;

- 5) What are your opinions on an ICW 'Best Practice' Design Guide to develop a document applicable to various industries and applications; what key elements should be included within the document?

General Comments

Please add any further comments you have in relation to ICWs and/or today's session.

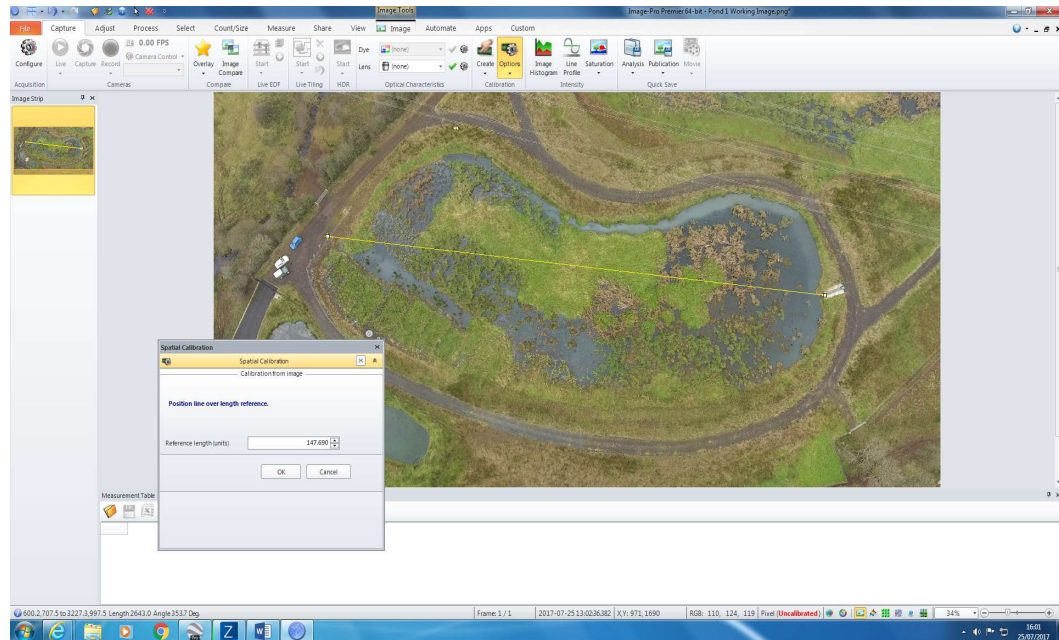
Contact Details:

Please insert your preferred contact details below if you wish to receive further information regarding today's session.

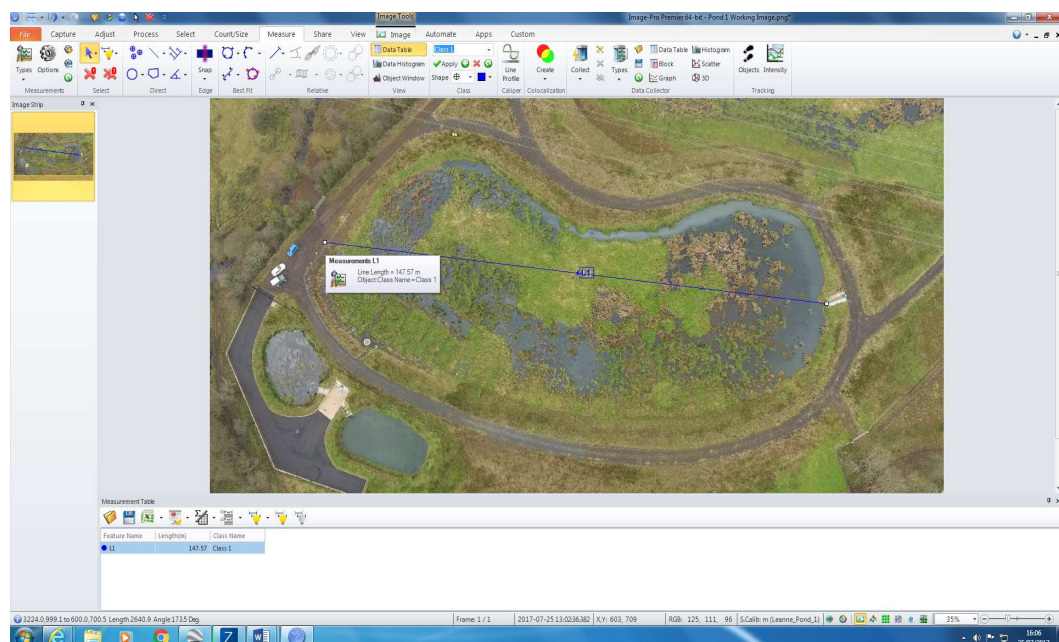
APPENDIX B: IMAGE PRO AREA ANALYSIS METHODS

Step 1: Open Image Pro, Select File and Open Image.

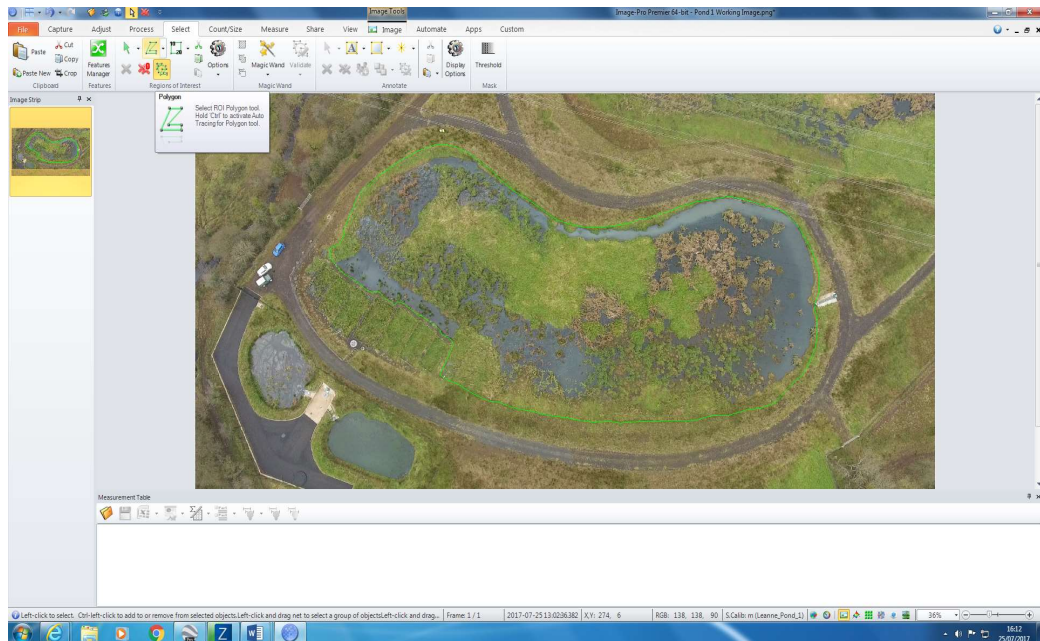
Step 2: Calibrate the image using known measurements from Google Earth Pro.



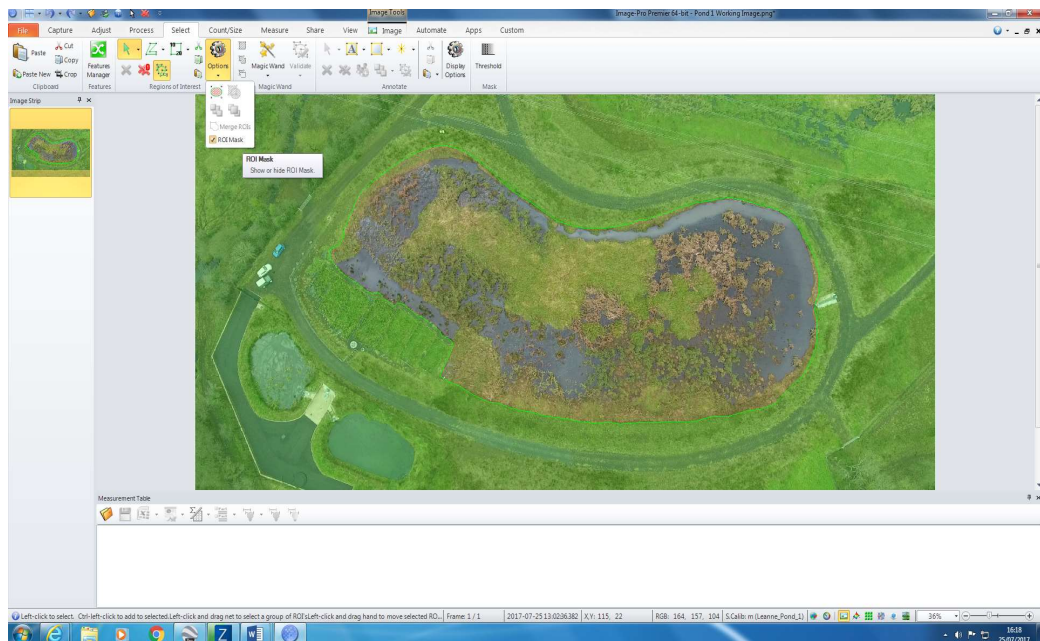
Step 3: Using the measuring tool, check the distance is correct. The image is now calibrated and ready for measurements to be taken.



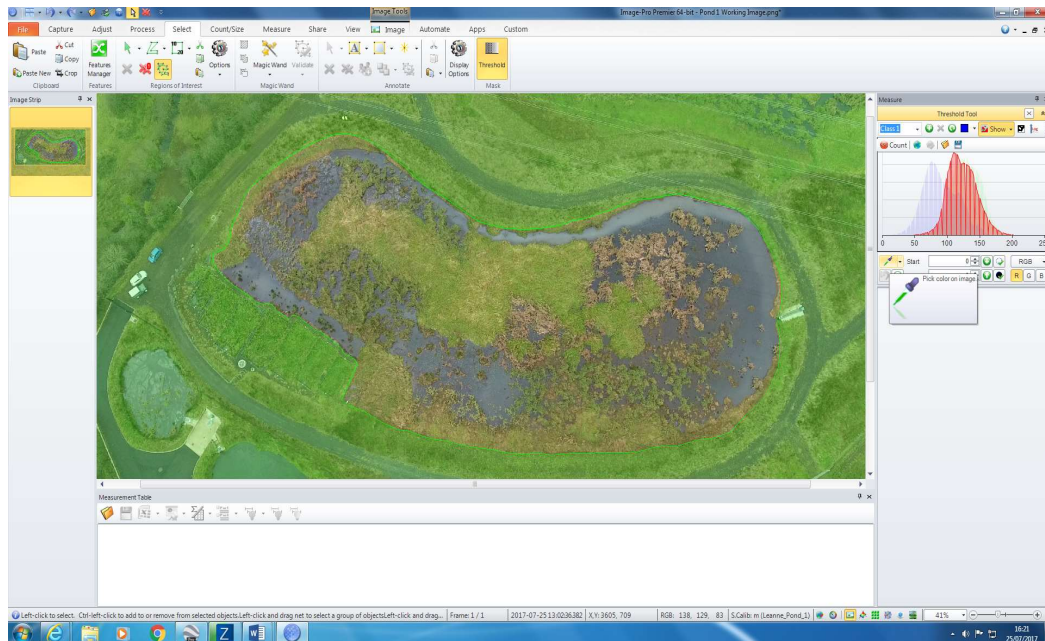
Step 4: Using the Polygon Selection Tool, select the area to be analysed as represented by the green line



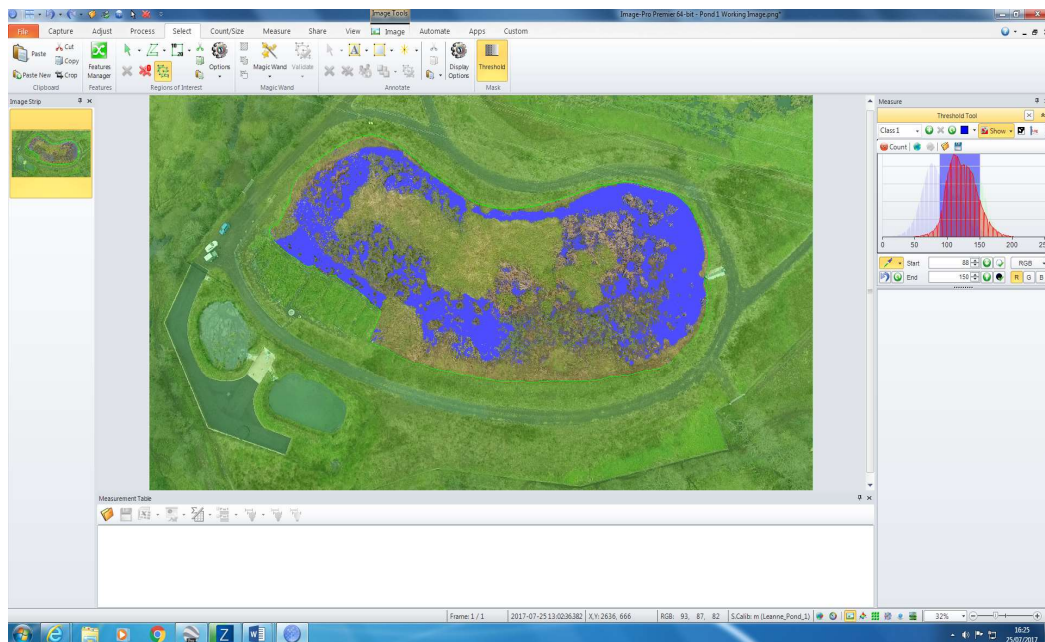
Step 5: Mask the remainder of the image by clicking Options, ROI Mask



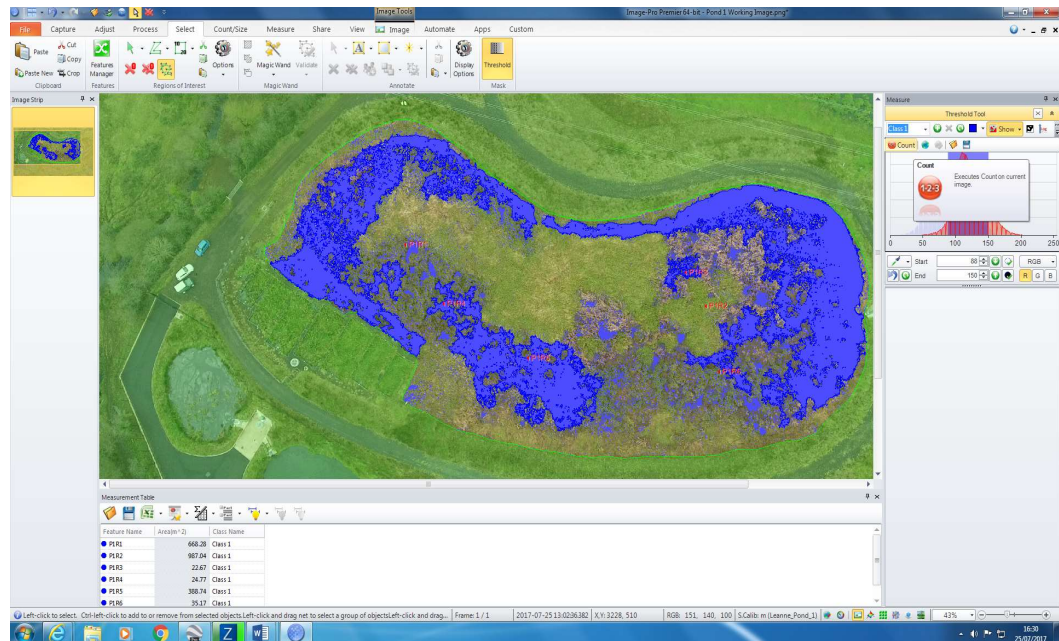
Step 6: In order to select the threshold, Select the threshold symbol and using the dropper tool, click the areas of the image measure.



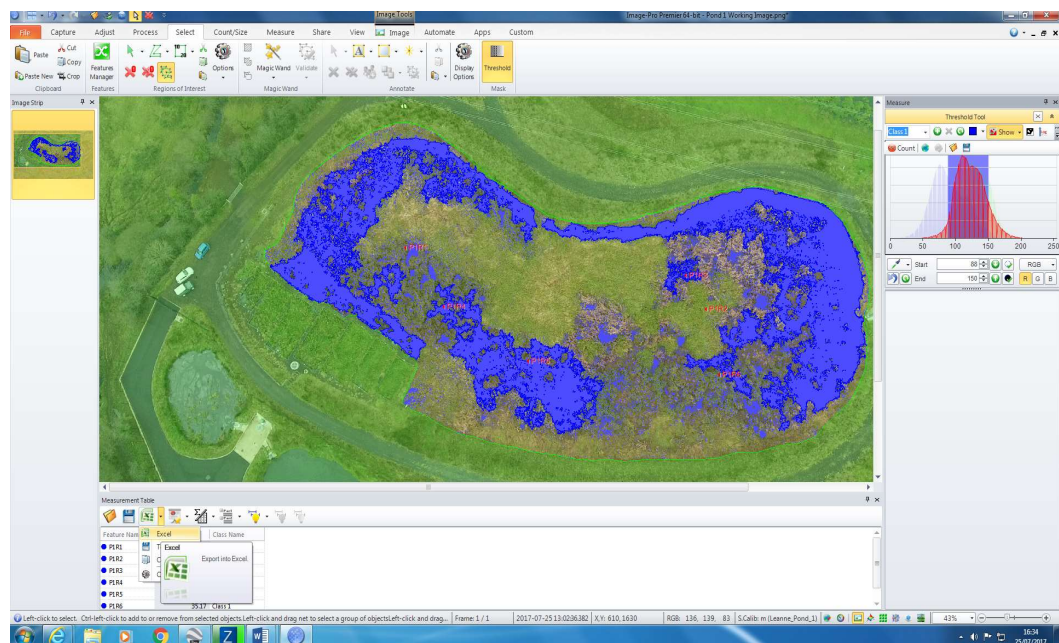
Step 7: The software will then select all pixels within the image that are of that threshold; continue selecting pixels until the area required is selected as below.



Step 8: Within the threshold window, select the 'Count' feature which will calculate the area of the thresholds selected and provide the areas in m² in a table at the bottom.



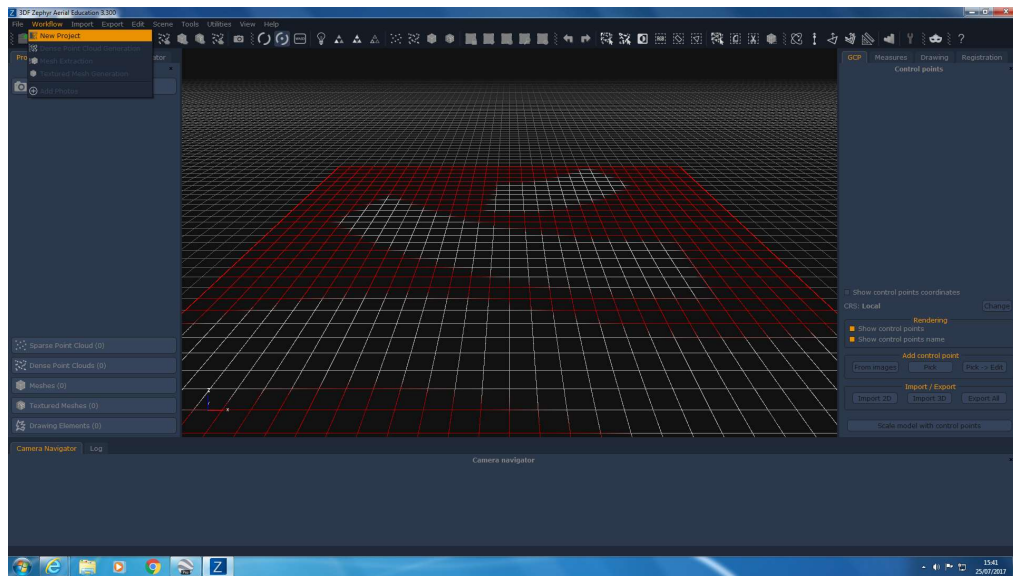
Step 9: The data table can then be exported to Excel for future use as demonstrated below.



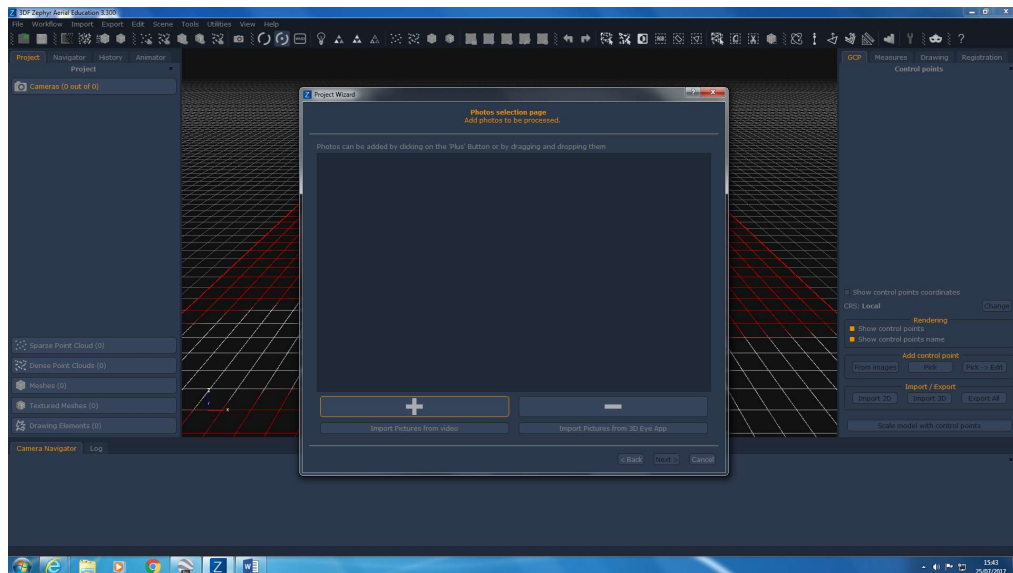
Step 10: To measure a new threshold, reset the threshold boundaries as below, and repeat the previous steps for a new threshold.

APPENDIX C: 3DF ZEPHYR AERIAL EDUCATIONAL 3.301 MODELLING METHODS

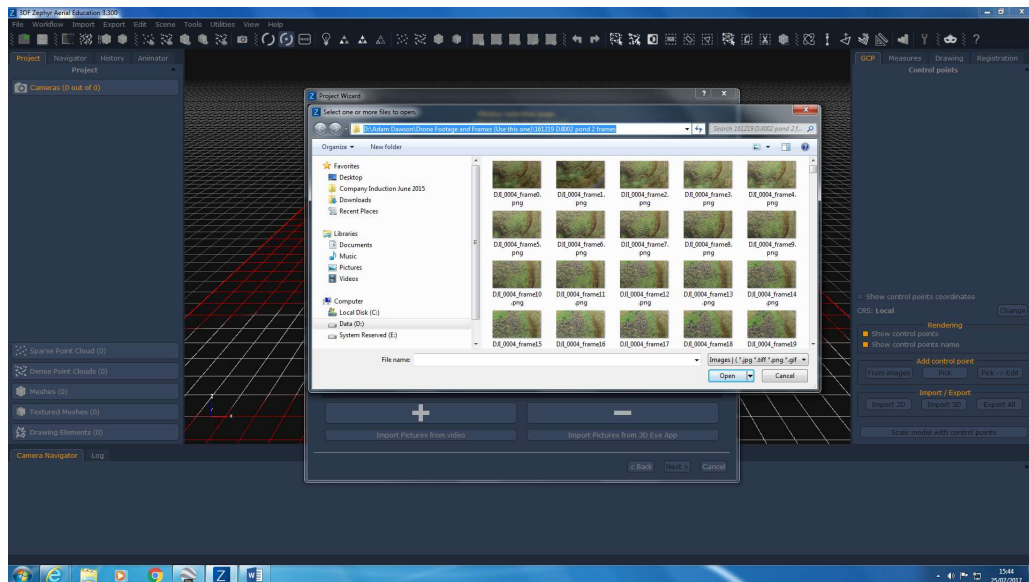
Step 1: Open Zephyr 3DF Software, click WorkFlow and select New Project.



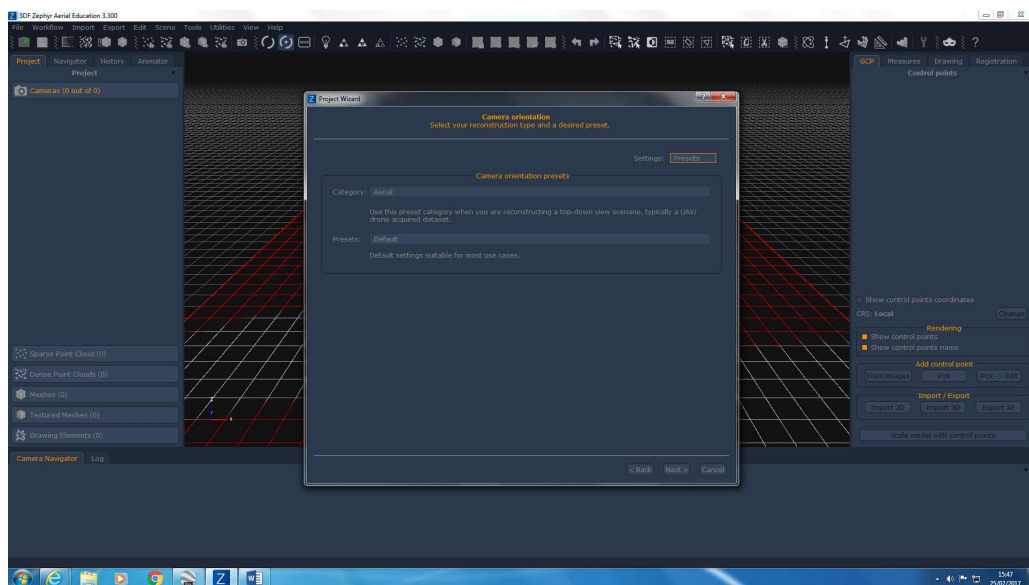
Step 2: Click Next, then select the '+' symbol to add new photos.



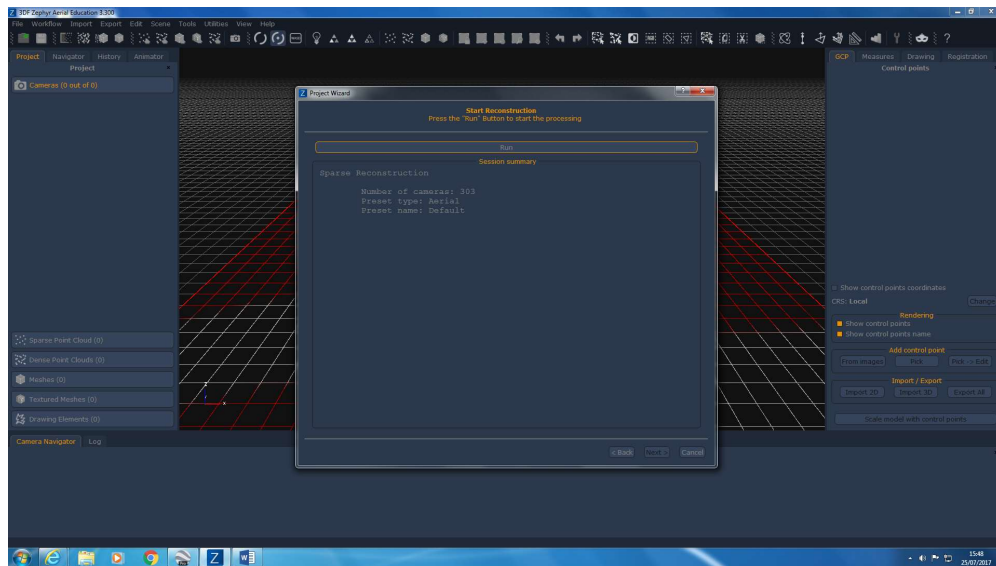
Step 3: Select images extracted from the 4K video to create the 3D model.



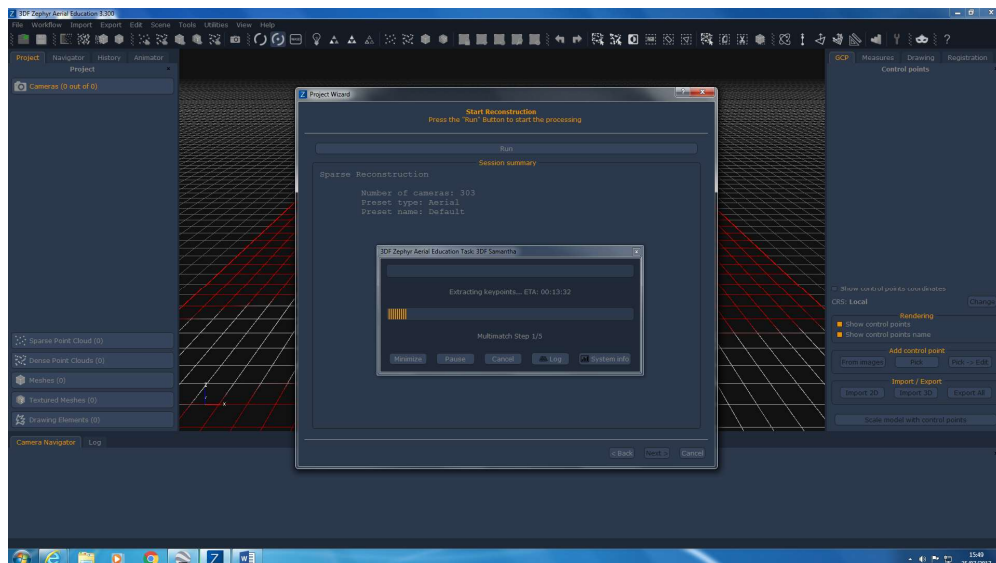
Step 4: Once uploaded, select next. The Camera Orientation screen will appear. Ensure the pre-sets selected are 'Aerial' and 'Default'.



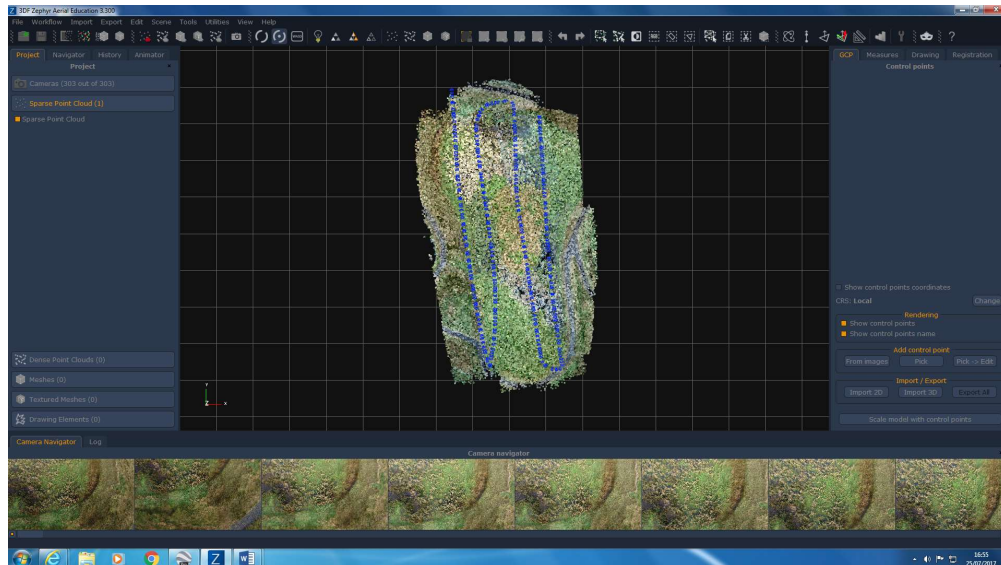
Step 5: Click next; the images are ready to be processed by selecting 'Run'.



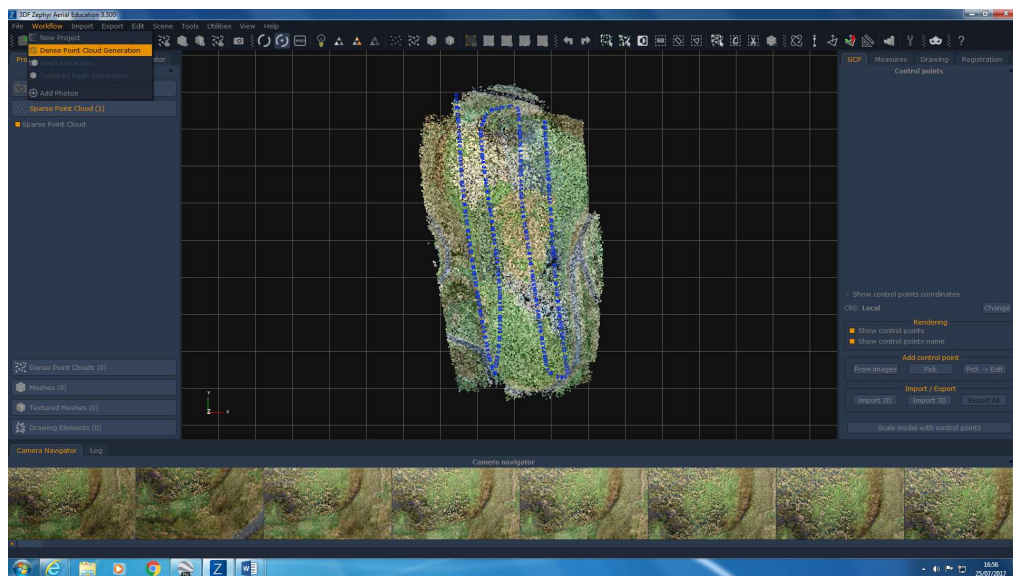
Step 6: The images are then extracted and uploaded onto the software.



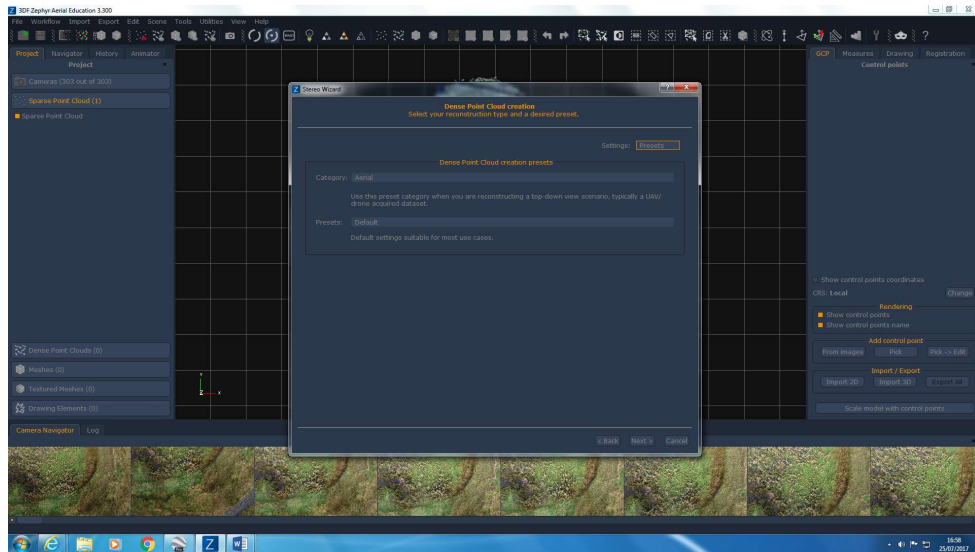
Step 7: Once the images are uploaded, click Finish and the reconstruction phase is complete as below. This is known as the 'Sparse Point Cloud'.



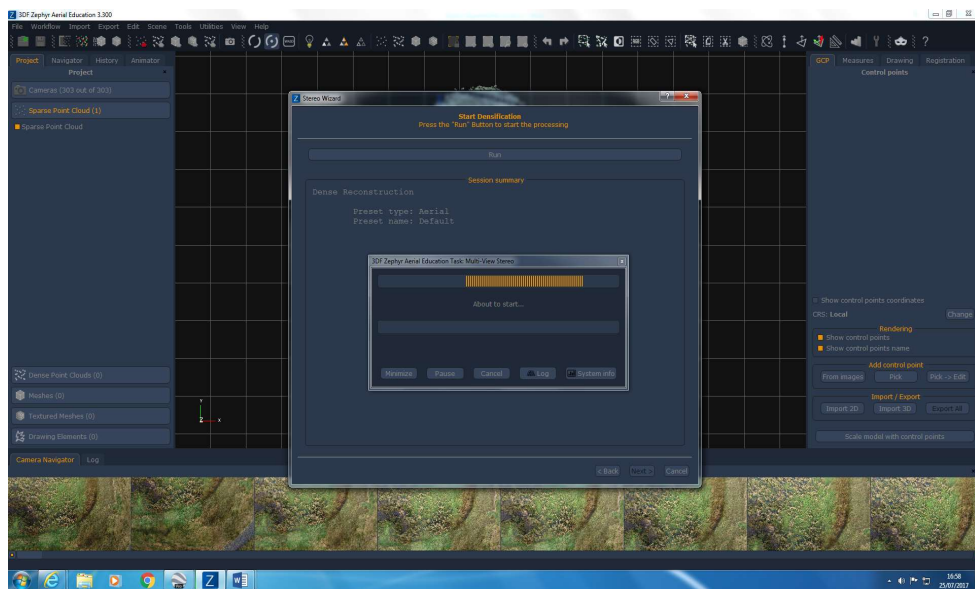
Step 8: Make a 'Dense Point Cloud' as shown below.



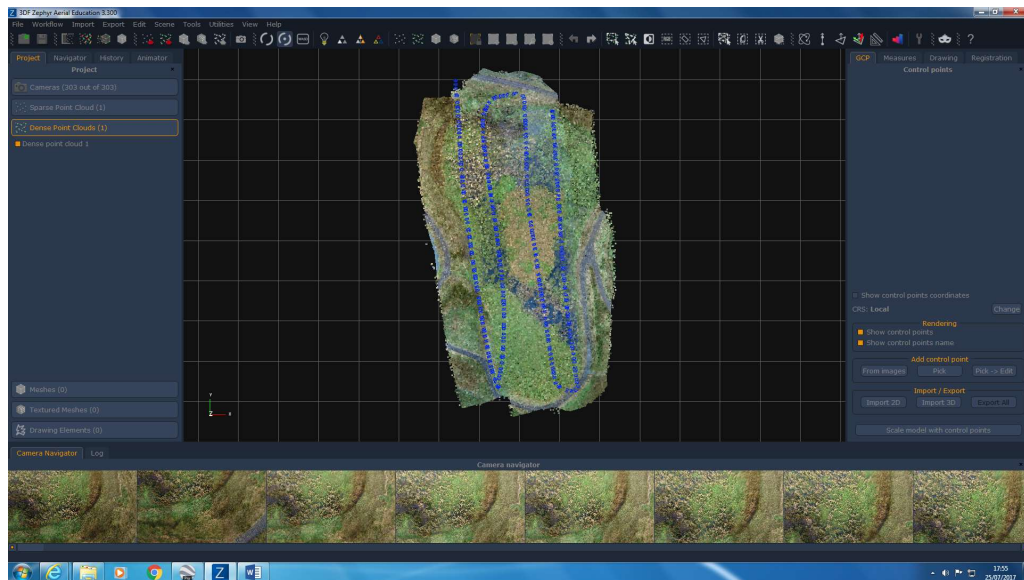
Step 9: Ensure pre-sets are set to 'Aerial' and 'Default'.



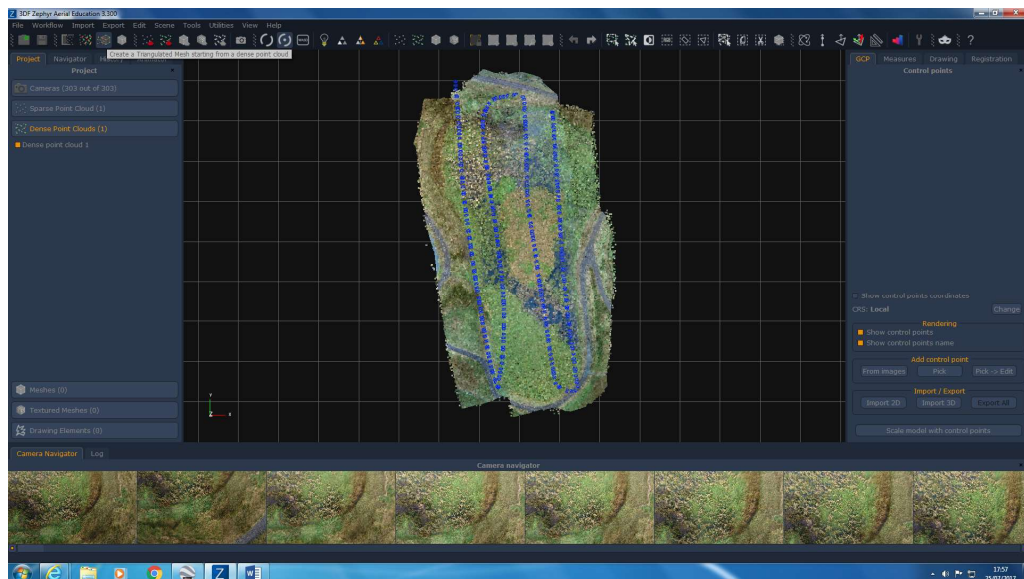
Step 10: Select 'Run' as previously then the software will begin processing the 'Dense Point Cloud'.



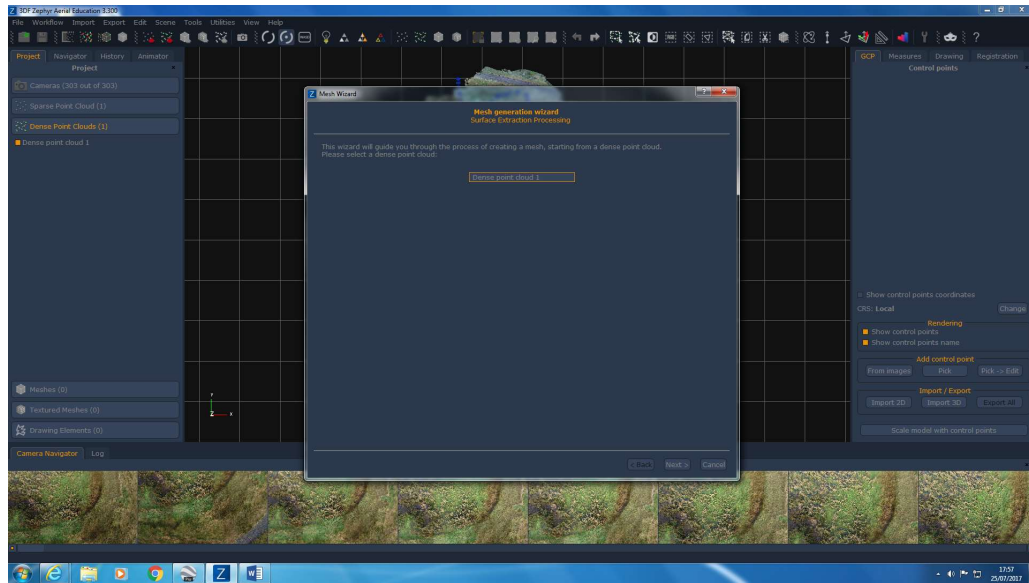
Step 11: Click 'Finish' and the 'Dense Point Cloud' will appear.



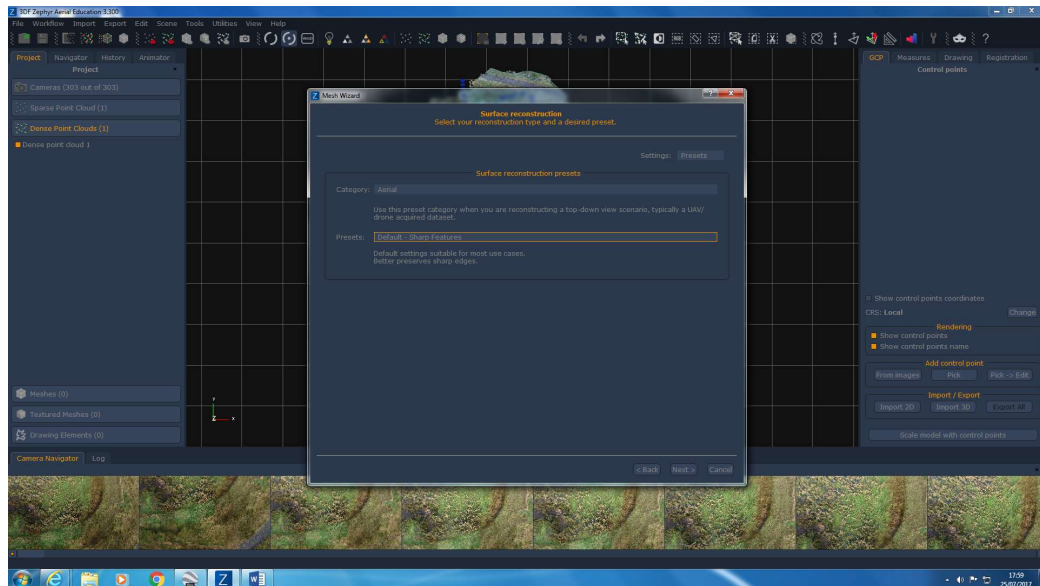
Step 12: Create a 'Triangulated Mesh' using the feature below.



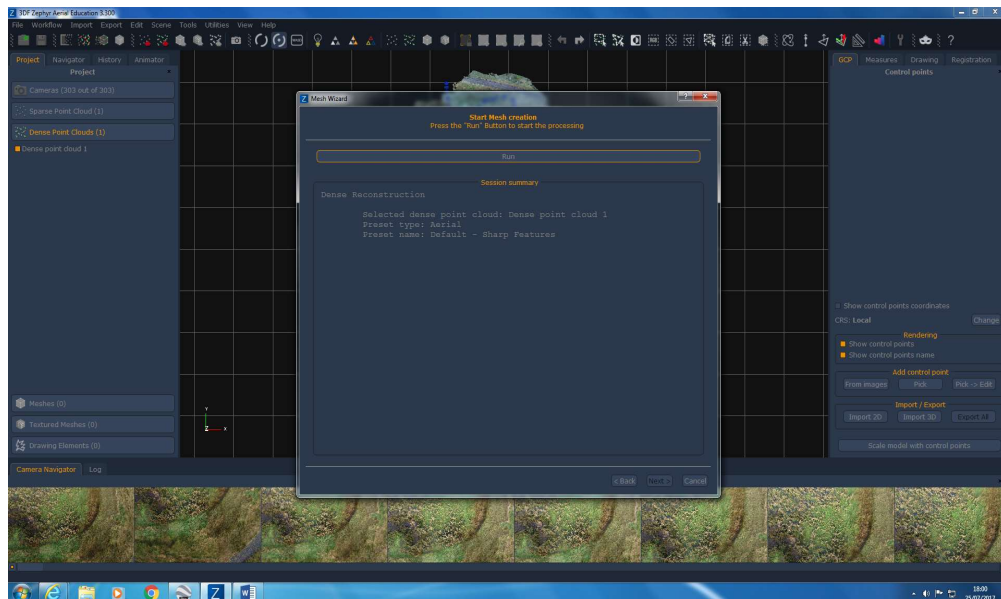
Step 13: Select the appropriate dense point cloud, in this case ‘Dense Point Cloud 1’.



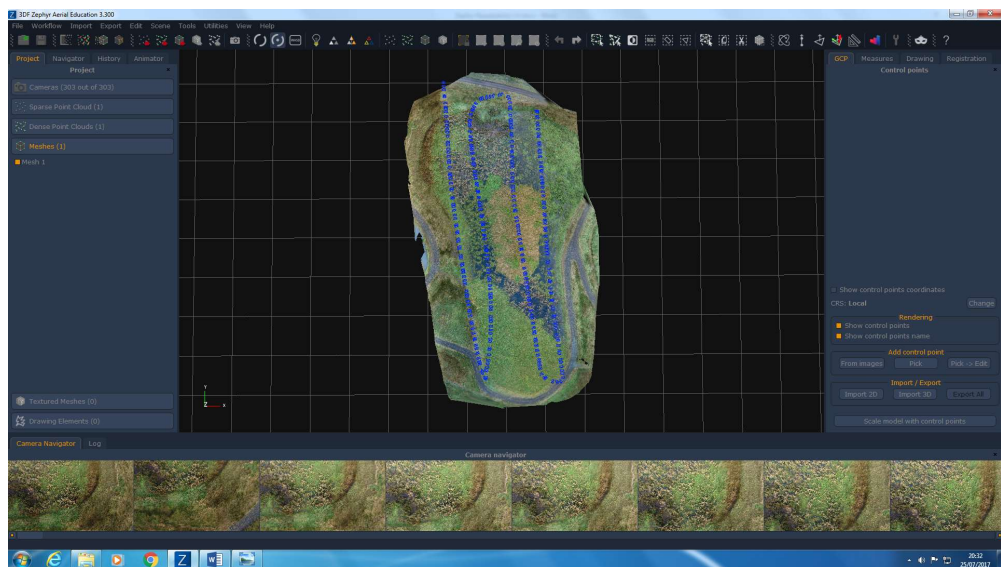
Step 14: Ensure the ‘Aerial’ and ‘Default – Sharp Edges’ pre-sets are selected and click next.



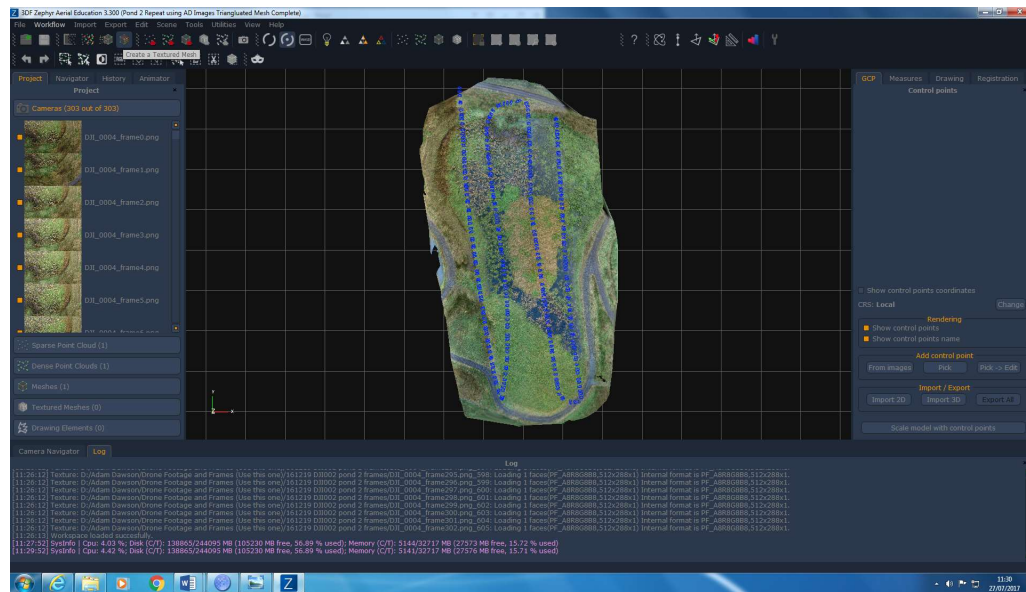
Step 15: Select 'Run' to process the image.



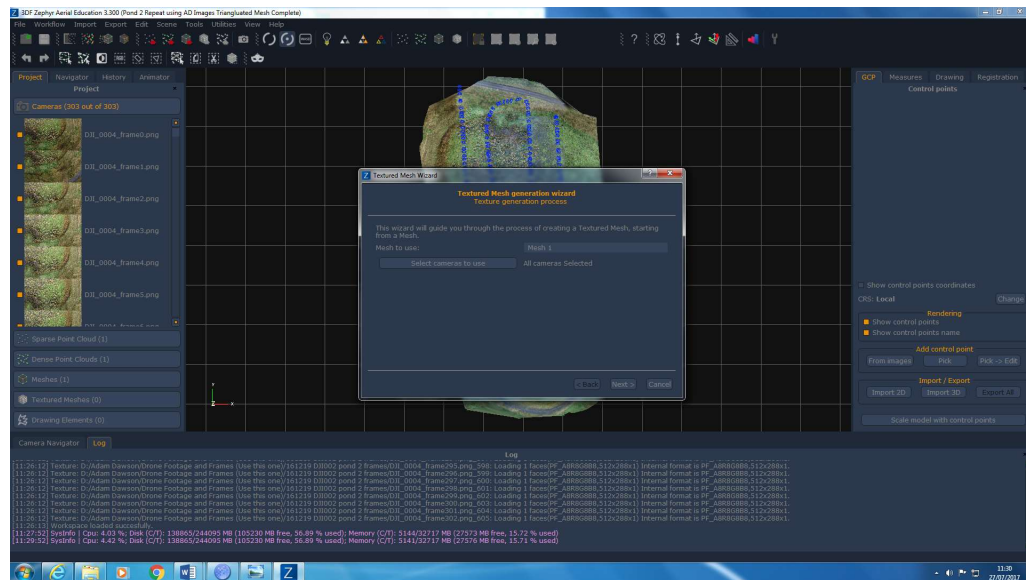
Step 16: Once finished, a triangulated mesh will appear as below.



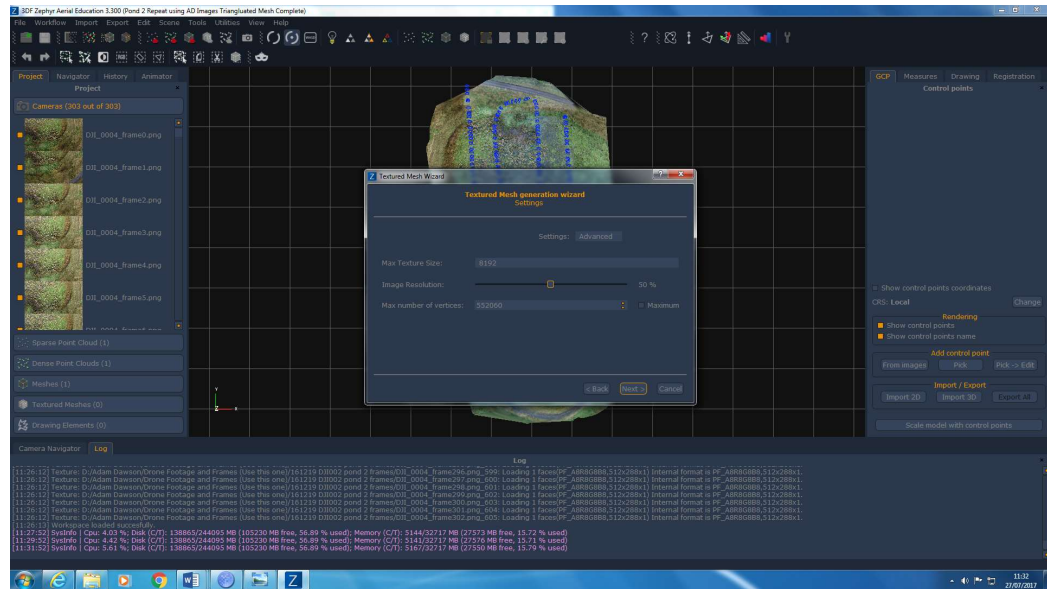
Step 17: The image is still in 2D format, and will require the development of a Textured Mesh to create 3D. This is done by clicking the ‘Create Textured Mesh’ symbol as below.



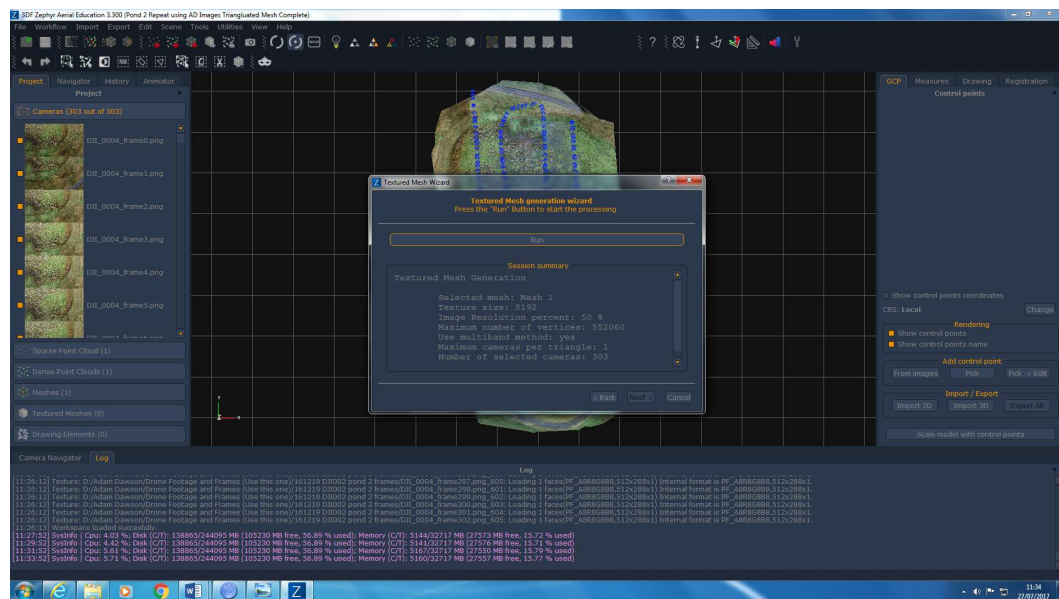
Step 18: The software will then ask which mesh and cameras should be used to create the textured mesh. In this case, the mesh is ‘Mesh 1’ and ‘All cameras’ are selected.



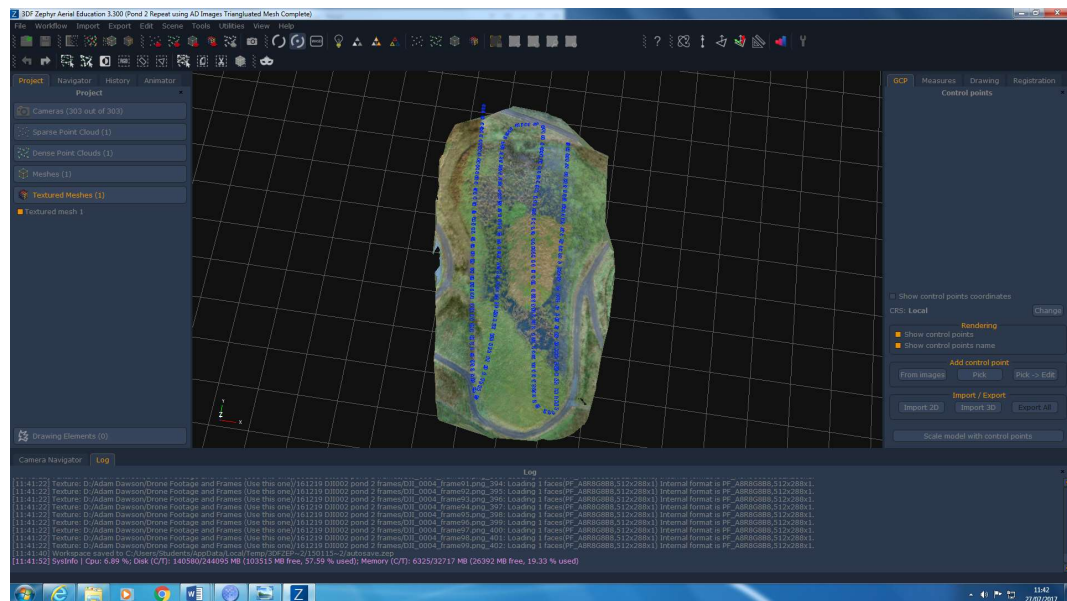
Step 19: Select 'next' and a 'settings' window will appear. Ensure 'Advanced' settings are selected and click next.



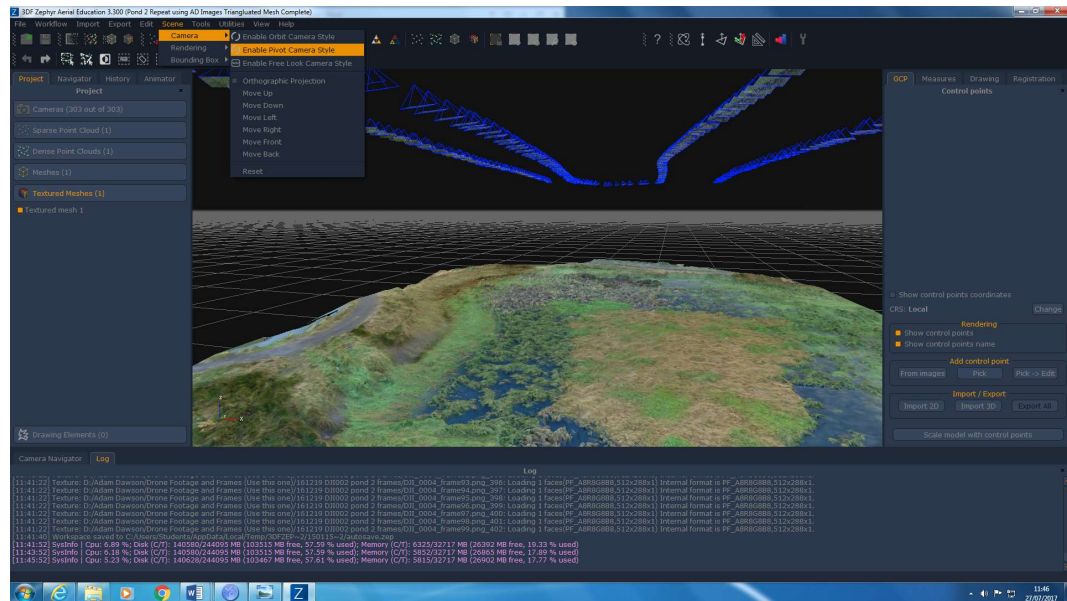
Step 20: The wizard will then show a summary of details that will be used to create the textured mesh. Check these are correct and click 'Run'.



Step 21: Once finished the textured mesh will look similar to the triangulated mesh as before.

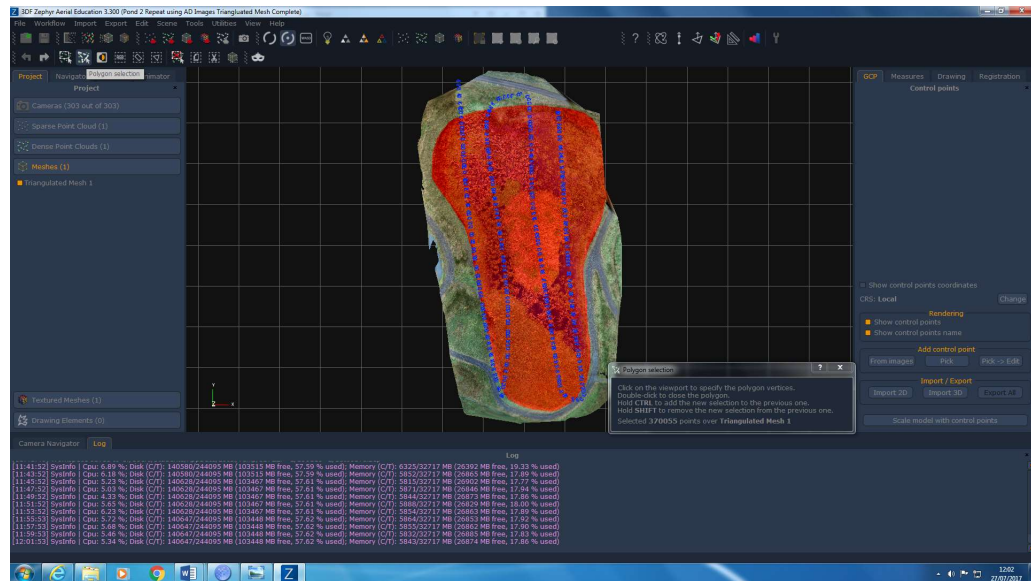


Step 22: However, by clicking 'Scene', 'Camera' then 'Enable Pivot Camera Style' you can navigate the 3D model and see the various textures created.

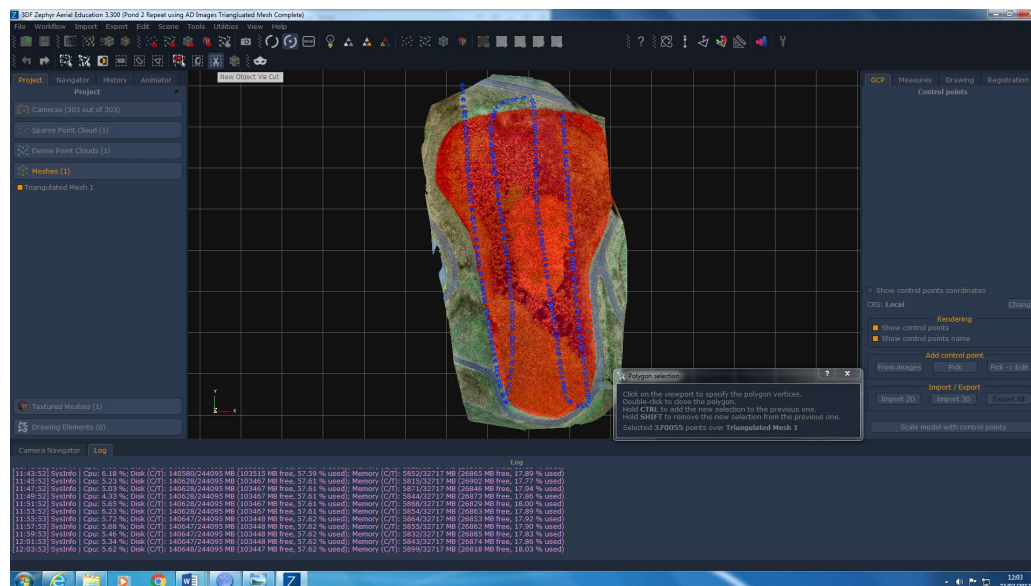


Once the model has been created it can then be used to make calculations.

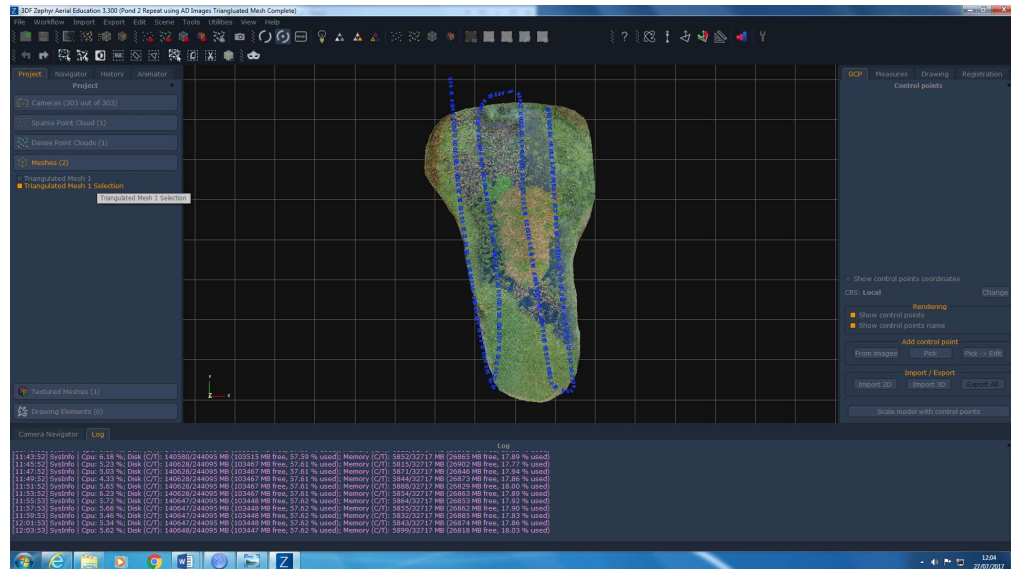
Step 23: The area of the model that needs to be calculated is selected using the poly line tool. Select the area within the triangulated mesh layer as opposed to the textured mesh layer as the triangulated mesh is the layer used to make calculations.



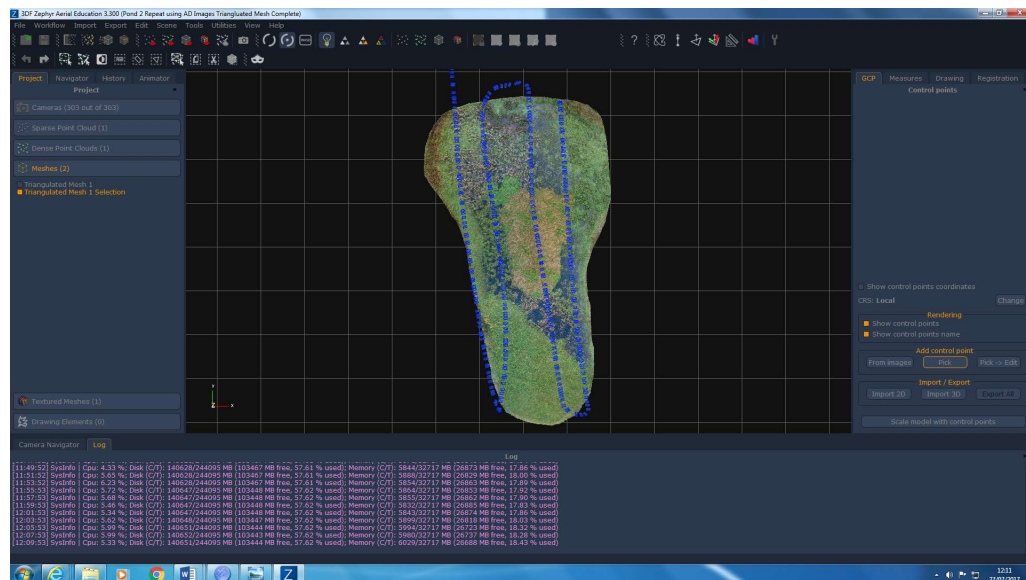
Step 24: The selected area can then be separated from the rest of the image into an individual layer using the 'new object via cut' tool.



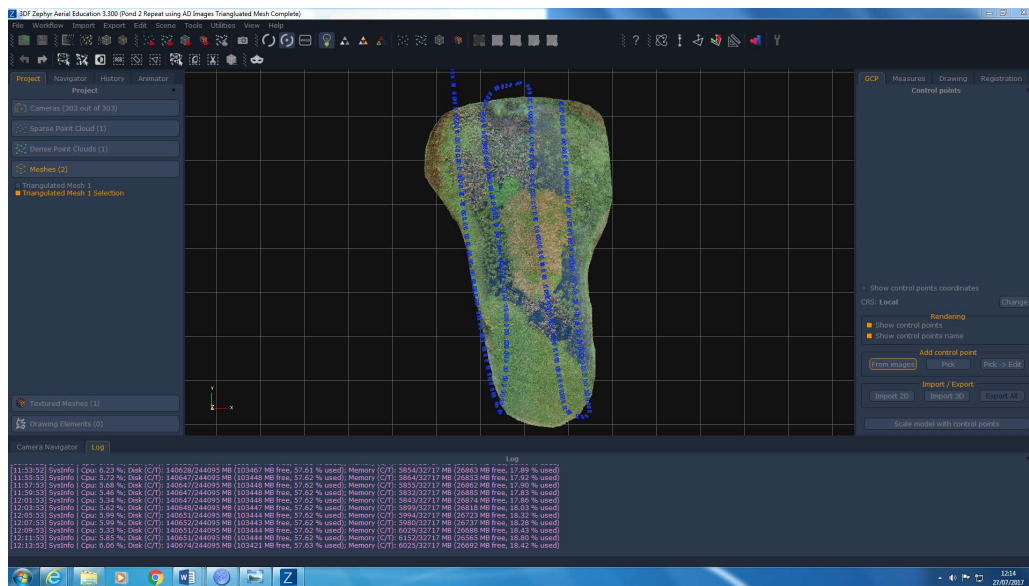
Step 25: This will create a new layer in the side panel which is more appropriate for calculating measurements.



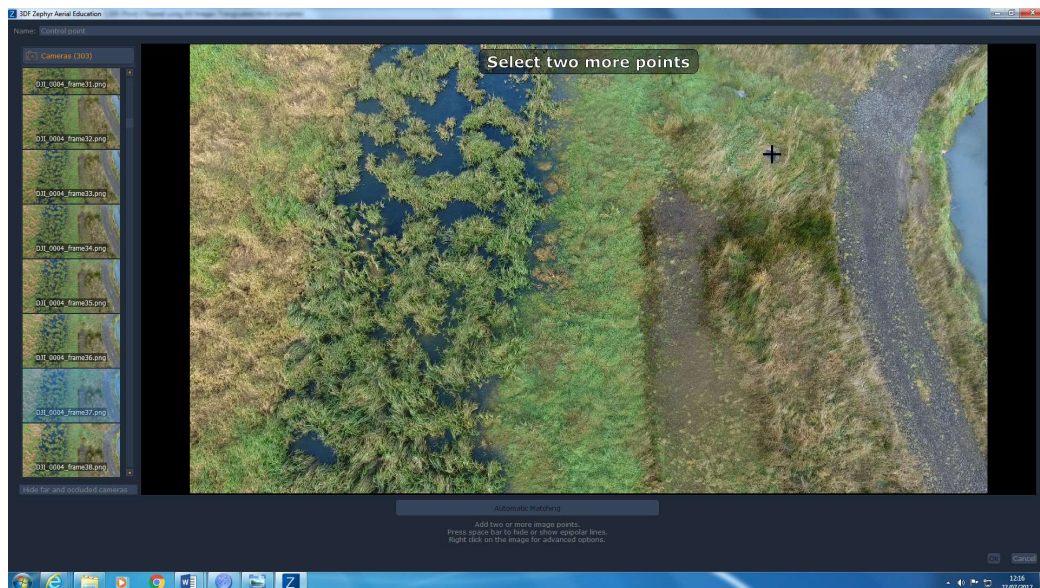
Step 26: Select control points on the map to allow for accurate calculation to be made. The easiest way to do this is by selecting 'pick' in the 'add control point' tool panel.



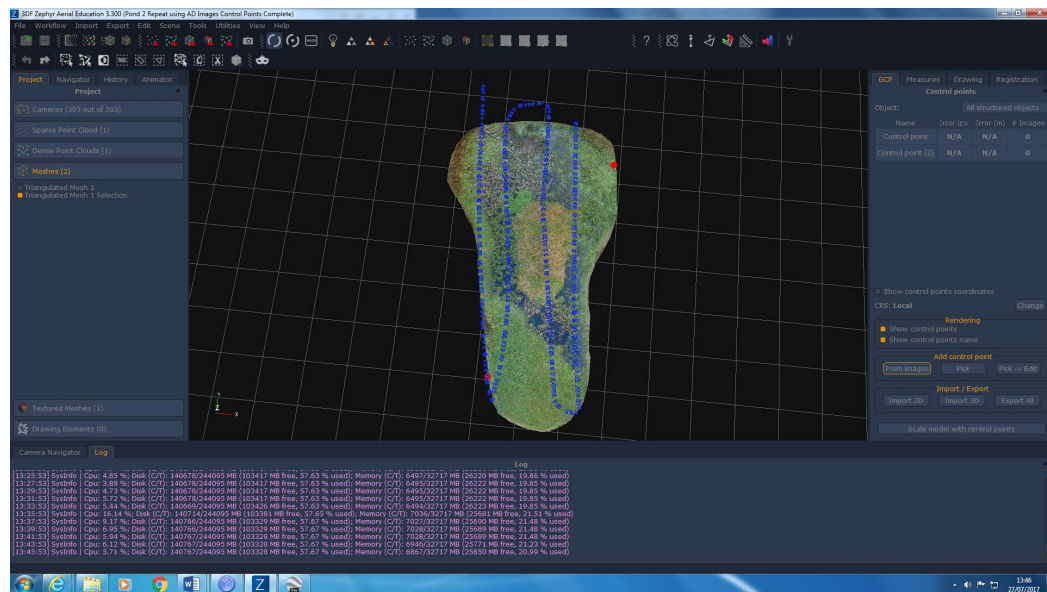
Step 27: A more accurate way is to select control points from the images.



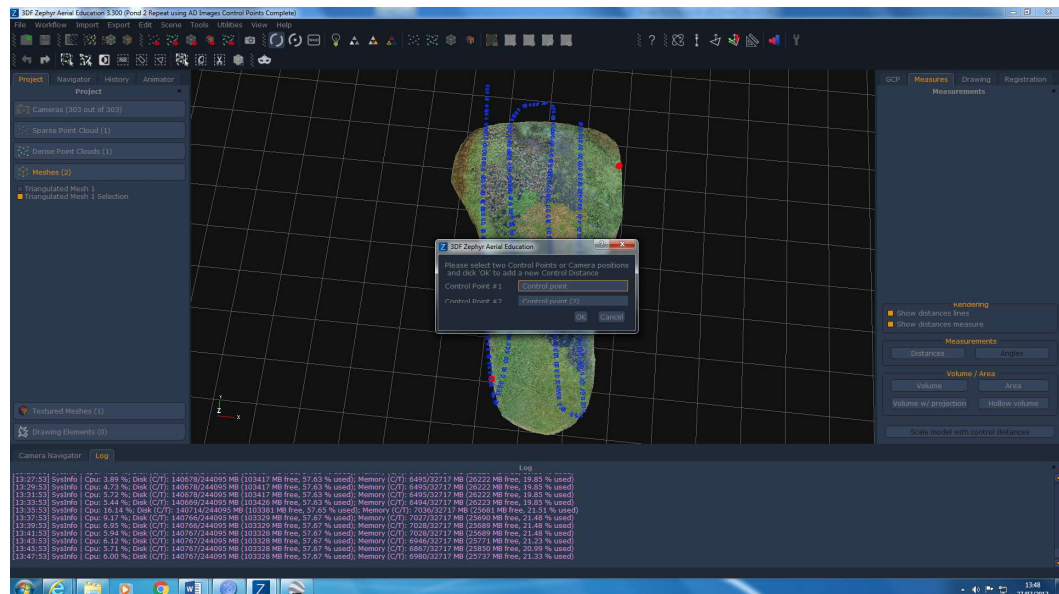
Step 28: This will allow you to select the same point on a number of images as shown below and will create the control point for the model.



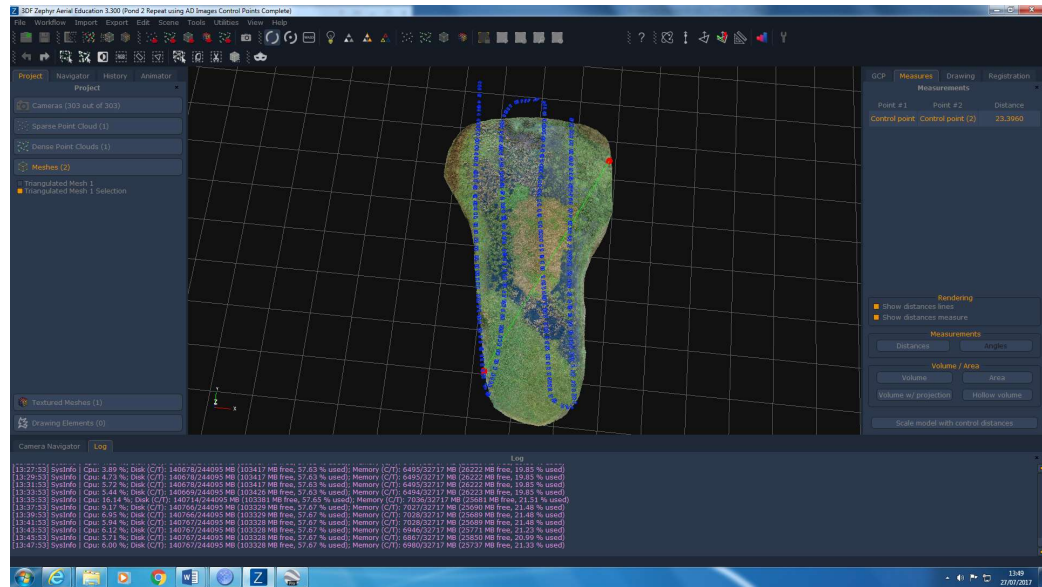
Step 29: Repeat the steps to create a number of control points as below.



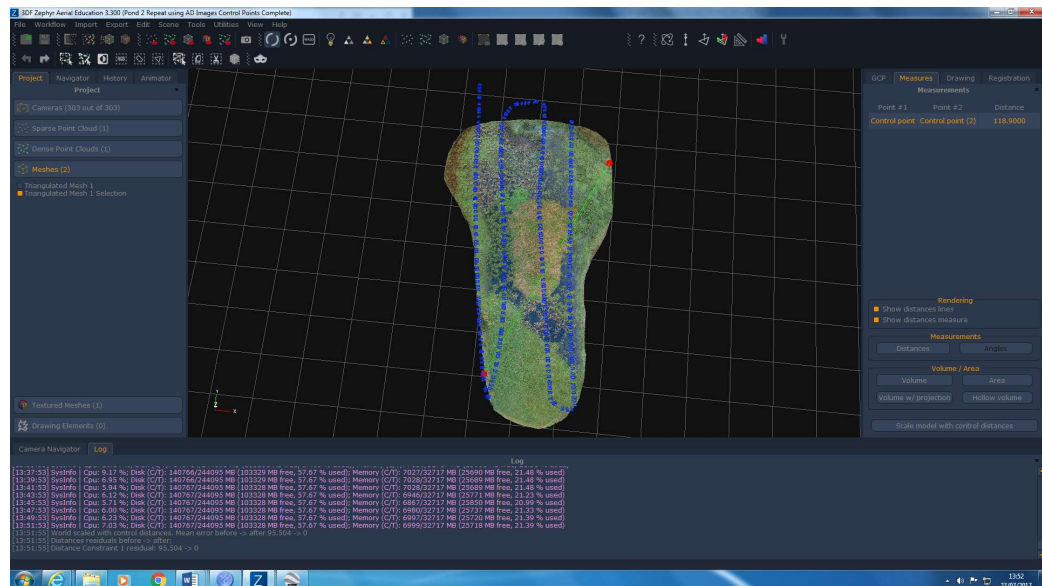
Step 30: The model can now be scaled. Select 'Measures' then 'Distance'. This will allow for the selection of control points to measure between.



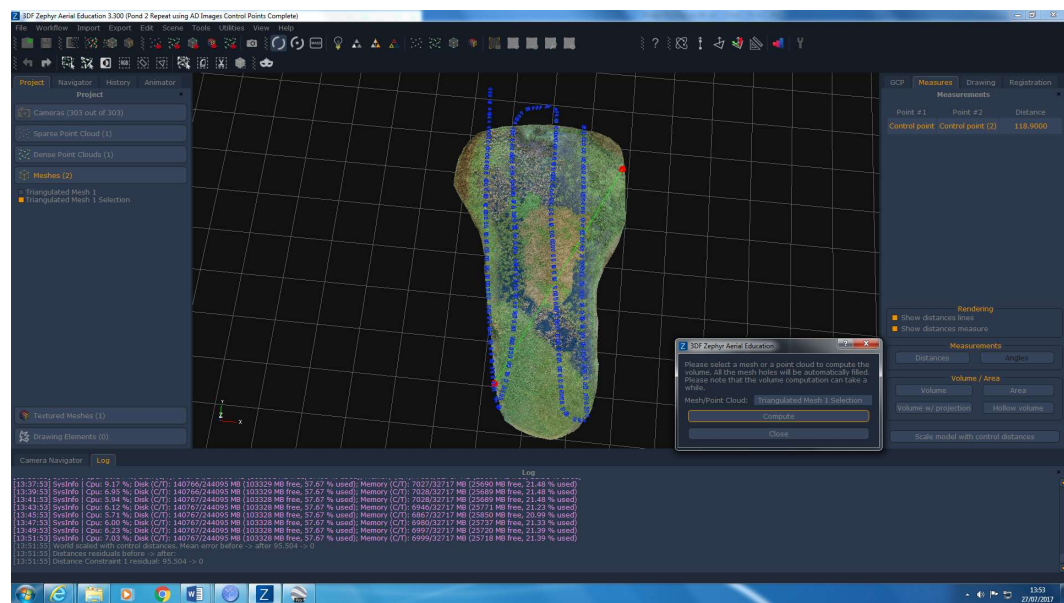
Step 31: The distance line will appear and an inaccurate distance will be displayed in the side panel as below.



Step 32: Using 'Scale model with control distances' enter the correct known distance between the control points.



Step 33: Calculate area and volume using the tools in the side bar.



APPENDIX D: STONEYFORD TEST RIG DATA TABLES

Biological Oxygen Demand (BOD)

Date	Inlet	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	WOC
26-Jan-16	104	35	4.1	2.24	0.92	9.04	15
04-Feb-16	86.4	11.2	3.1	2.68	2.12	0.96	15
09-Feb-16	88.8	8	1.44	1.96	1.68	1.36	15
18-Feb-16	158.2	14.4	3.28	4.11	3.96	3.88	15
23-Feb-16	72.8	8.9	3.36	2.24	2.58	1.41	15
03-Mar-16	41	9.9	1.8	1.88	0.96	0.6	15
08-Mar-16	121	3.7	2.16	1.41	1.62	1.08	15
16-Mar-16	127	76	0.7	2.8	0.84	3.96	15
24-Mar-16	137.2	194	4.4	9.2	0.95	2.3	15
31-Mar-16	150	76.6	1.7	2.94	1.98	2.05	15
05-Apr-16	44	16.8	2.1	1	0.96	1.62	15
12-Apr-16	62	126	3.2	2.9	1.35	2.28	15
19-Apr-16	344	64	1.2	2.3	0.78	2	15
28-Apr-16	352	55.3	5.5	8.94	3.36	2.88	15
05-May-16	273	48.4	2	2.24	3.56	1.96	15
10-May-16	224	33.4	5.94	3.18	3.32	3.72	15
19-May-16	131.6	27.6	10.6	6	4.4	3.08	15
24-May-16	201	18	12.3	9.5	2.9	2.8	15
02-Jun-16	145.6	23.4	12.1	6.2	5.32	4.34	15
07-Jun-16	191.8	48	20.3	28.8	8.5	13.6	15
16-Jun-16	130	43.5	36	8.2	2.32	5	15
21-Jun-16	189.6	13	6	6.6	3.5	2.92	15
30-Jun-16	208.6	60	9	12.7	2.28	2.96	15
05-Jul-16	35.2	24.4	5.88	4.9	3.3	2.1	15
26-Jul-16	114.1	4.8	4.8	18.4	5	3.44	15
04-Aug-16	141	18.4	10.5	32	9.24	3.4	15
09-Aug-16	189	12.4	10.3	7.8	7.4	4	15
18-Aug-16	175	14.6	11.1	14.8	11.4	3.09	15
23-Aug-16	189	16	7.8	26	14.28	7	15
01-Sep-16	147	7.7	8.4	13.6	5.04	2.76	15
06-Sep-16	108	63	31	58.4	43	11.4	15
15-Sep-16	222.6	152.6	33.6	38.4	13	11.3	15
22-Sep-16	159.2	27.3	3.4	7.6	6.6	1.4	15
29-Sep-16	175	4.9	<0.29	4	2	1.84	15
12-Oct-16	189	19.1	4.96	6	5.2	2.32	15
26-Oct-16	128.8	20.86	2.16	1.85	0.63	2.35	15
02-Nov-16	170.8	14.4	12.2	1.8	6.6	1.2	15
10-Nov-16	88.2	46				1.2	15
17-Nov-16	106.4	11.2	6	1.7	10.5	3.28	15
24-Nov-16	54	33.4	8.4	1.7	9	40	15
01-Dec-16	138.6	47.2	7.7	2.6	4.4	2.28	15
08-Dec-16	148	34.5	4.1	3.92	2.87	3.22	15
15-Dec-16	163.8	16.4	10.8	7.6	8.7	4.2	15

05-Jan-17	153	15.36	7.4	4.55	24.4	2.84	15
12-Jan-17	132	11.2	3.5	2.2	7.5	3.32	15
19-Jan-17	140	12.3	2.3	2.4	1	0.3	15
26-Jan-17	170.4	6.16	6.36	2.85	2.12	1.32	15
02-Feb-17	128.8	8.4	4.2	5.04	2.94	2.2	15
09-Feb-17	138.6	13.9	4.32	5.25	1.32	0.72	15
16-Feb-17	137.9	105	1.5	2.24	1.96	1.33	15
23-Feb-17	132	16.6	3.4	7.28	2.84	12.36	15
02-Mar-17	100.8	11.48	3.78	2.32	2.22	1.3	15
09-Mar-17	81.2	7	6.16	1.12	2.08	2.46	15
16-Mar-17	107	4.2	1.76	0.96	0.9	0.3	15
23-Mar-17	55.3	10	3.01	1.41	0.87	0.9	15
30-Mar-17	149	7.2	3	4.13	1.61	1.82	15
06-Apr-17	210	8.54	6.44	3	2.5	0.66	15
13-Apr-17	208.6	19.04	7.56	4.48	5.04	9.38	15
20-Apr-17	210	259	30.4	3.6	3.22	1.54	15
27-Apr-17	211	77	3.68	3.6	4.69	2.52	15
04-May-17	132	68.8	6.1	2.52	7.44	5.1	15
18-May-17	151	29	4.55	2.1	1.75	2	15
25-May-17	212	51.8	10.36	2.56	3.2	2.3	15
01-Jun-17	438	146	79.2	14.4	10.3	11.4	15
08-Jun-17	352	6.5	4.6	3.8	2.3	2.4	15
15-Jun-17	196	5.7	5.32	5.4	2.59	2.88	15
22-Jun-17	183.4	7.56	7.1	5.32	9.38	3.92	15
29-Jun-17	159.6	8.2	5.4	4.2	4.3	3.64	15
06-Jul-17	83	5.95	5.32	4.41	3.43	3.96	15
11-Jul-17	193.2	51.2	56.6	28.9	3.71	10.08	15

Suspended Solids (SS)

Date	Inlet	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	WOC
26-Jan-16	41	4	10	1.4	5	4	25
04-Feb-16	70	1.4	6	3	3	5	25
09-Feb-16	64	1.4	3	3	1.4	5	25
18-Feb-16	19	1.4	3	3	3	3	25
23-Feb-16	30	5	1.4	1.4	1.4	3	25
03-Mar-16	46	4	1.4	1.4	1.4	1.4	25
08-Mar-16	48	1.4	1.4	1.4	1.4	5	25
16-Mar-16	47	350	204	152	26	6	25
24-Mar-16	55	1830	254	446	23	10	25
31-Mar-16	41	99	156	29	15	11	25
05-Apr-16	41	19	205	21	8	11	25
12-Apr-16	50	1340	167	74	3	5	25
19-Apr-16	440	340	40	104	13	7	25
28-Apr-16	470	22	10	8	4	1.4	25
05-May-16	230	93	7	6	11	7	25
10-May-16	248	62	16	11	15	15	25
19-May-16	182	38	12	4	9	1.4	25
24-May-16	151	51	29	150	10	8	25
02-Jun-16	174	99	17	350	31	21	25
07-Jun-16	106	336	30	70	32	34	25
16-Jun-16	111	176	25	176	13	11	25
21-Jun-16	174	130	24	25	14	9	25
30-Jun-16	172	896	16	40	1.4	4	25
05-Jul-16	28	52	16	52	20	8	25
26-Jul-16	71	29	38	290	23	20	25
04-Aug-16	210	200	80	344	11	18	25
09-Aug-16	197	48	43	29	33	56	25
18-Aug-16	46	100	60	42	56	18	25
23-Aug-16	56	76	16	96	58	14	25
01-Sep-16	105	92	32	45	31	11	25
06-Sep-16	26	144	16	88	26	14	25
15-Sep-16	120	624	23	30	35	25	25
22-Sep-16	148	160	32	40	20	16	25
29-Sep-16	124	132	42	4	68	4	25
12-Oct-16	26	44	24	<2.8	24	6	25
26-Oct-16	50	248	128	12	16	12	25
02-Nov-16	124	554	38	10	22	7	25
10-Nov-16	50	430				1.4	25
17-Nov-16	34	42	20	4	44		25
24-Nov-16	74	311	59	5	17	148	25
01-Dec-16	46	248	4	8	<2.8	6	25
08-Dec-16	74	184	14	4	20	1.4	25
15-Dec-16	72	36	22	6	18	4	25

05-Jan-17	70	40	18	8	30	24	25
12-Jan-17	42	12	38	22	24	24	25
19-Jan-17	58	24	12	10	20	8	25
26-Jan-17	212	23	18	12	<2.8	7	25
02-Feb-17	98	24	6	12	16	8	25
09-Feb-17	56	20	19	16	4	4	25
16-Feb-17	52	76	20	24	12	9	25
23-Feb-17	48	26	184	10	18	10	25
02-Mar-17	58	41	7	5	5	8	25
09-Mar-17	59	85	9	4	<2.8	3	25
16-Mar-17	90	42	18	<2.8	18	8	25
23-Mar-17	76	54	6	4	<2.8	<2.8	25
30-Mar-17	109	39	19	22	12	15	25
06-Apr-17	232	44	129	26	<2.8	18	25
13-Apr-17	324	46	42	6	4	5	25
20-Apr-17	332	9020	430	20	12	5	25
27-Apr-17	144	236	23	16	3	4	25
04-May-17	100	736	70	26	14	7	25
18-May-17	113	108	24	8	12	4	25
25-May-17	55	800	70	20	8	11	25
01-Jun-17	78	11560	246	176	41	25	25
08-Jun-17	110	58	12	266	4	9	25
15-Jun-17	230	42	26	94	4	9	25
22-Jun-17	174	6	30	304	48	18	25
29-Jun-17	152	20	26	66	50	20	25
06-Jul-17	64	30	10	35	16	16	25
11-Jul-17	80	846.7	3790	124	32	180	25

Ammonia (NH₃-N)

Date	Inlet	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	WOC
26-Jan-16	15.02	16.25	9.65	0.84	0.12	0.12	3
04-Feb-16	7.56	11.33	10.87	4.61	2.59	1.4	3
09-Feb-16	16.33	13.26	9.96	3.39	1.88	1.33	3
18-Feb-16	6.7	17.71	9.8	2.56	0.12	0.14	3
23-Feb-16	12	13.28	10.04	3.58	0.96	0.47	3
03-Mar-16	9.07	16.87	8.52	1.82	0.08	0.08	3
08-Mar-16	23.15	8.76	8.38	2.57	1.37	1	3
16-Mar-16	20.92	17.01	7.57	0.08	0.04	0.08	3
24-Mar-16	24.6	21.24	6.86	0.31	0.015	0.07	3
31-Mar-16	21.17	22.98	9.72	0.07	0.09	0.14	3
05-Apr-16	16.72	18.98	12.96	2.4	0.12	0.12	3
12-Apr-16	24.62	14.51	2.32	0.015	0.015	0.05	3
19-Apr-16	32.8	15.54	0.17	0.04	0.015	0.07	3
28-Apr-16	38.2	25.67	0.11	0.05	0.07	0.14	3
05-May-16	35.71	25.15	0.1	0.05	0.015	0.06	3
10-May-16	38.77	24.12	1.87	0.015	0.07	0.08	3
19-May-16	19.94	18.67	4.66	0.015	0.06	0.04	3
24-May-16	32.51	15.21	4.79	0.19	0.09	0.08	3
02-Jun-16	32.15	22.53	0.67	0.1	0.12	0.11	3
07-Jun-16	27.15	24.31	0.29	0.08	0.15	0.015	3
16-Jun-16	42.32	23.15	0.39	0.31	0.05	0.015	3
21-Jun-16	39.09	19.81	14.94	4.81	0.07	0.015	3
30-Jun-16	36.02	26.57	12.07	1.76	0.07	0.05	3
05-Jul-16	9.75	21.12	13.31	7.6	0.57	0.015	3
26-Jul-16	32.37	21.43	10.27	2.5	1.69	0.37	3
04-Aug-16	37.54	18.85	12.36	7.91	5.68	3.33	3
09-Aug-16	38.33	20.87	13.68	5.34	1.24	0.6	3
18-Aug-16	48.63	25.28	12.59	12.03	2.22	0.32	3
23-Aug-16	17.82	25.61	14.84	13.79	5.65	1.29	3
01-Sep-16	39.66	23.38	9.03	12.77	3.25	0.88	3
06-Sep-16	15.67	19.78	21.86	14.77	7.15	1.72	3
15-Sep-16	19.02	17.47	12.02	14.81	7.58	3.89	3
12-Oct-16	40.89	32.12	22.01	13.22	6.54	2.03	3
26-Oct-16	48.36	24.06	17.88	14.63	10.14	6.73	3
02-Nov-16	47.76	23.11	13.54	14.86	10.46	3.73	3
10-Nov-16	16.59	12.05				3.73	3
17-Nov-16	22.01	15.31	14.61	12.59	5.09	7.56	3
24-Nov-16	22.53	19.99	19.05	12.72	14.23	10.5	3
01-Dec-16	26.64	24.82	23.58	10.95	17.1	11.91	3
08-Dec-16	31.46	24.1	26.53	15.85	17.95	13.07	3
15-Dec-16	28.35	23.69	26.66	18.72	17.84	13.8	3
05-Jan-17	35.57	4.77	23.62	17.56	16.65	12.84	3
12-Jan-17	26.11	15.2	18.89	17.88	16.88	12.82	3

19-Jan-17	29.4	12.57	21.39	17.93	16.01	12.68	3
26-Jan-17	28.32	11.95	23.86	19.68	16.62	10.99	3
02-Feb-17	20.99	10.98	16.55	18.76	15.63	10.94	3
09-Feb-17	21.87	13.55	14.72	13.91	11.82	9	3
16-Feb-17	27.18	36.63	14.44	12.6	10.25	6.31	3
23-Feb-17	32.72	21.82	19.57	12.4	9.82	3.61	3
02-Mar-17	21.03	18.15	16.18	10.44	8.44	5.52	3
09-Mar-17	20.29	12.76	13.36	8.75	7.18	3.34	3
16-Mar-17	19.98	9.47	15.1	3.88	1.73	<0.03	3
23-Mar-17	18.02	12.68	13.36	2.15	0.83	0.06	3
30-Mar-17	19.49	10.79	13.35	1.32	0.15	<0.03	3
06-Apr-17	21.89	8.74	17.09	0.17	0.08	<0.03	3
13-Apr-17	25.96	10.86	18.58	0.93	0.39	0.13	3
20-Apr-17	31.51	12.04	21.73	4.27	0.14	<0.03	3
27-Apr-17	35.42	22.52	24.33	0.98	0.23	0.1	3
04-May-17	28.27	32.16	23.28	1.38	0.16	0.09	3
18-May-17	33.74	14.16	22.79	8.12	2.65	0.05	3
25-May-17	32.65	28.94	20.94	7.63	0.18	0.05	3
01-Jun-17	41.97	26.62	28.56	4.46	1.33	0.17	3
08-Jun-17	29.54	3.06	19.14	4.18	2.49	0.62	3
15-Jun-17	32.97	4.86	15.93	5.55	2.63	0.26	3
22-Jun-17	35.97	5.08	21.74	8.69	0.55	0.13	3
29-Jun-17	31.91	2.57	21.74	16.82	1.55	0.07	3
06-Jul-17	31.93	4.56	16.91	13.81	7.12	7.09	3
11-Jul-17	31.16	13.36	19.27	11.16	7.83	2.07	3

Chemical Oxygen Demand (COD)

Date	Inlet	Pond 1	Pond 2	Pond 3	Pond 4	Pond 5
26-Jan-16	166	56	35.6	24.8	23.6	28.4
04-Feb-16	256	27.5	17.9	17.4	15.9	22
09-Feb-16	220	27.4	20.7	20.7	19.8	19.2
18-Feb-16	63.3	40.3	14.4	23.8	14.3	16.3
23-Feb-16	120	48.4	24	25	23.9	22.3
03-Mar-16	144	54.6	25.2	25.3	25.2	25.5
08-Mar-16	268	23.6	15.2	13.5	25.4	4.75
16-Mar-16	211	181	63	52.1	17.4	20.3
24-Mar-16	259	432	63.7	102	26.1	30.3
31-Mar-16	219	174	54.8	27.3	38	30.7
05-Apr-16	92.5	73.7	49	39.3	38.6	39
12-Apr-16	267	230	39.3	31.5	17.1	24.2
19-Apr-16	762	107	25.3	26.5	22	33.1
28-Apr-16	247	134	33.8	40.7	28.7	38.2
05-May-16	580	134	30.7	23.8	36.4	35.5
10-May-16	530	130	49	39.7	44.1	48
19-May-16	314.8	157	72.2	61.3	58.4	64.5
24-May-16	442	143	73.2	77.9	57.4	50.9
02-Jun-16	385	170	76.1	92	51.7	59.6
07-Jun-16	329	293	112	98.7	69.9	112
16-Jun-16	323	241	202	173	78.2	75.5
21-Jun-16	483	224	85.4	96.4	80.6	82.2
30-Jun-16	470	350	96.8	102	85.2	71.7
05-Jul-16	127	241.2	96.3	134	92.7	97.5
26-Jul-16	324	98.2	117	301	131	139
04-Aug-16	351	115	108	572	114	105
09-Aug-16	540	92	101	103	129	125
18-Aug-16	505	104	109	137	147	102
23-Aug-16	322	74.8	88.8	130	156	153
01-Sep-16	335	113	103	137	124	90.2
06-Sep-16	146	111	66.4	94.6	111	128
15-Sep-16	275	314	103	97.6	115	118
22-Sep-16	430	124	71.2	96.8	111	83.7
29-Sep-16	430	97.8	51.6	84.7	97.5	63.9
12-Oct-16	280	88.2	71.4	67.4	68.1	52.5
26-Oct-16	318	221	39.9	58.9	57.4	53.8
02-Nov-16	314	242.4	82.6	50.3	65.5	45.5
10-Nov-16	174	291				50.7
24-Nov-16	236	287	88.1	70.9	67.9	287
01-Dec-16	315	311.2	48.8	48.9	85.7	51
08-Dec-16	333	361	60.5	44.7	61.7	60.6
15-Dec-16	263	61.6	60.4	53.6	62.9	59.5
05-Jan-17	295	54.9	52.4	55.1	84.1	50.6

12-Jan-17	289	66.2	55.7	48	54.9	53.6
19-Jan-17	299	51	41	38	33.5	34.1
26-Jan-17	909	47.8	42.8	48.6	37.1	30.8
02-Feb-17	277	48.3	38.4	44.3	35	42.7
09-Feb-17	245	57	37.8	30.8	28.9	32.2
16-Feb-17	237	221	28.1	30.2	28	24.3
23-Feb-17	301	66	40.2	33.2	28	35.4
02-Mar-17	207	68.4	43.5	38.4	37.1	36.6
09-Mar-17	172	77.5	36.7	34.3	34.3	26.7
16-Mar-17	249	62.8	35.8	28.7	41	37.3
23-Mar-17	161	69.6	36.6	36.1	31.8	23.9
30-Mar-17	270	37.2	28.3	22.9	15.4	10.3
06-Apr-17	511	63.9	80.3	55.4	34.2	24.4
13-Apr-17	434	103	71.2	56.7	56.3	45.7
20-Apr-17	595		209	40.3	31.5	25.6
27-Apr-17	492	604	39.7	47.6	86	24.3
04-May-17	286	397	52.1	49.4	40.9	40.5
18-May-17	352	295	61.8	55	61.6	57.5
25-May-17	363	187	68.2	58.3	65.3	56.3
01-Jun-17	464	484	142	112	59.2	65.1
08-Jun-17	302	57.8	73.3	88	71.4	61.3
15-Jun-17	462	45.4	58.1	82	58.1	51.1
22-Jun-17	348	28.4	74.4	88.4	38.8	58.7
29-Jun-17	324	63.2	88.8	93.6	71.6	80
06-Jul-17	228	428	66.8	92.4	74.8	108.4
11-Jul-17	424	350	54.8	79.2	76.8	147.2

**APPENDIX E: AVERAGE WEEKLY WEATHER DATA CORRESPONDING TO SAMPLE
DATES**

Week Ending	Week Number	Total Precipitation (mm)	Average Wind Speed (m/s)	Average Humidity (%)	Average Temperature (°C)
26-Jan-16	1	38.6	3.8	92.7	3.4
04-Feb-16	2	14	5.9	86.7	8.5
09-Feb-16	3	45.8	7.6	86.1	6.3
18-Feb-16	4	27.4	6.6	87.1	5.7
23-Feb-16	5	18.4	3.9	84.7	3.3
03-Mar-16	6	46.4	5.0	89.0	4.3
08-Mar-16	7	11.4	3.3	81.8	2.9
16-Mar-16	8	33	4.5	85.5	4.2
24-Mar-16	9	16	4.1	80.3	7.9
31-Mar-16	10	0.4	2.8	83.6	6.6
05-Apr-16	11	27	5.0	80.9	7.1
12-Apr-16	12	36.2	4.2	87.2	6.4
19-Apr-16	13	32.2	5.1	83.1	6.1
28-Apr-16	14	11.6	3.6	82.9	6.6
05-May-16	15	0.2	3.6	72.4	7.7
10-May-16	16	20	5.2	77.3	6.5
19-May-16	17	2.8	5.0	75.3	11.3
24-May-16	18	0.4	4.1	70.8	11.5
02-Jun-16	19	51.6	3.7	83.8	11.0
07-Jun-16	20	1	3.0	79.5	11.8
16-Jun-16	21	0	3.2	74.0	15.5
21-Jun-16	22	59.6	2.7	87.0	16.1
30-Jun-16	23	12.8	3.7	82.8	13.5
05-Jul-16	24	18	3.8	81.2	13.9
26-Jul-16	27	28.2	3.7	79.3	15.4
04-Aug-16	28	22.2	3.4	80.9	17.2
09-Aug-16	29	45.4	2.7	83.2	14.2
18-Aug-16	30	7.2	5.0	80.6	15.5
23-Aug-16	31	8.6	4.7	82.7	14.9
30-Aug-16	32	23	4.5	82.9	16.6
01-Sep-16	33	20	2.8	82.5	14.7
06-Sep-16	34	26.6	4.4	83.6	15.5
15-Sep-16	35	39.2	5.5	84.5	16.1
22-Sep-16	36	8.2	2.9	84.8	14.2
29-Sep-16	38	3	4.8	83.9	12.1
12-Oct-16	40	47.6	4.5	85.4	10.5
26-Oct-16	42	0.8	3.1	90.0	10.8
02-Nov-16	43	10.6	3.1	84.0	6.1
10-Nov-16	44	61.8	3.9	91.6	7.9
17-Nov-16	45	15.2	4.4	91.2	3.9
24-Nov-16	46	1.8	2.3	87.6	3.5
01-Dec-16	47	1	2.6	87.4	5.8

08-Dec-16	48	2.2	4.8	91.7	9.7
15-Dec-16	49	28.2	3.9	91.8	4.2
05-Jan-17	53	11.4	5.0	87.0	5.7

APPENDIX F: STONEYFORD TEST RIG DATA TABLES

Biological Oxygen Demand (BOD)

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1	WOC
09-Aug-16	189	180.6	149	279	136	142	131.6	173.6	352	15
18-Aug-16	175	446.6	183.5	189.5	119	116.2	127.4	152.6	184.8	15
23-Aug-16	189	130.2	216	128	170	142	150	158	142	15
01-Sep-16	147	308	176	176	124.6	121.8	120	144	226	15
06-Sep-16	108	110	139	100	188	154	145.6	144	124	15
15-Sep-16	222.6	136	197	128.4	135.6	189	142.8	274	217	15
22-Sep-16	159.2	72	89.6	62	77	72	99	95.2	76.3	15
29-Sep-16	175	109	84	102.9	121.8	124.6	133	136	121	15
06-Oct-16		24.4	4.4	5.8	5.53	2.17			165.6	15
12-Oct-16	189	101.2	140.5	101	128.5	106	150	183.5	172	15
19-Oct-16	114.8	70.7	77	77	71.4	56	77	72.8	114	15
26-Oct-16	128.8	70	65	68	74	96.8	103	120	110	15
02-Nov-16	170.8	111	119	105	118	127	151	161	145	15
10-Nov-16	88.2	50	62	39.9	62	73	63	68	109.9	15
17-Nov-16	106.4	99.4	88	84	102	105.6	90.4	114	8.32	15
24-Nov-16	54	114.8	115	116.2	141.4	156	172	182	154	15
01-Dec-16	138.6	102.4	118.4	116.9	111.3	122.5	126.7	158.2	123.2	15
08-Dec-16	148	106.5	126	123.2	113.4	109.2	127.4	116.9	143	15
15-Dec-16	163.8	94.5	106.4	103.6	106.4	94.5	95.2	98	119.2	15
05-Jan-17	153	117	141.5	127	111.5	110.5	116	133.5	148.4	15
12-Jan-17	132	92.4	97.3	96.6	111.3	121.1	117.6	121.8	105	15
19-Jan-17	140	88	101	101	103	108	108	100	117	15
26-Jan-17	170.4	141.4	211.4	154	146	153	153	142	164	15
02-Feb-17	128.8	54.4	55.3	77	63.7	93.8	90.3	85	87.5	15
09-Feb-17	138.6	82.4	79	72	113	112	74.2	125.3	194	15
16-Feb-17	137.9	31.5	96.6	96.8	88.8	130	109.2	109.9	135.1	15
23-Feb-17	132	98	91	96	85	117	106	119	135	15
02-Mar-17	100.8	75.6	90	83	74	42	87	67.9	112	15
09-Mar-17	81.2	60	64	54	97	61	59.5	50.4	74.9	15
16-Mar-17	107	96	76	80	80	96	87	140	148	15
23-Mar-17	55.3	40.2	35	21.7	23.8	12.6	26.6	22.2	50.4	15
30-Mar-17	149	150	124	116	142	148	225	163.8	115	15
06-Apr-17	210	79.8	93.8	88.2	99.4	95.2	115	138.6	100.8	15
13-Apr-17	208.6	116.2	123.2	158.2	168	165.2	162.4	186.2	125	15
20-Apr-17	210	105	121.8	118	180.6	147	148.4	173	179.2	15
27-Apr-17	211	104	129	98	130	146	142	146	114	15

Suspended Solids (SS)

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1	WOC
09-Aug-16	197	59	55	1450	82	49	79	73	792	25
18-Aug-16	46	2824	63	59	58	50	54	52	50	25
23-Aug-16	90	36	25	26	36	35	39	19	20	25
01-Sep-16	105	3196	54	44	36	33	38	36	226	25
06-Sep-16	26	20	17	21	24	40	20	16	15	25
15-Sep-16	120	23	27	23	32	32	32	30	20	25
22-Sep-16	148	22	36	12	30	40	40	44	29	25
29-Sep-16	124	21	20	21	22	46	30	37	26	25
06-Oct-16		140	56	6	32	4			26	25
12-Oct-16	26	16	20	24	16	10	40	38	24	25
19-Oct-16	48	4	4	5	11	10	8	19	24	25
26-Oct-16	50	18	10	14	10	30	24	38	36	25
02-Nov-16	124	24	12	28	16	22	20	22	36	25
10-Nov-16	50	8	5	11	15	12	4	8	132	25
17-Nov-16	34	6	17	18	24	16	30	34	985	25
24-Nov-16	74	30	35	35	51	68	61	83	368	25
01-Dec-16	46	12	16	24	24	18	22	46	42	25
08-Dec-16	74	26	36	34	38	36	38	46	50	25
15-Dec-16	72	24	28	16	36	32	26	28	42	25
05-Jan-17	70	16	20	32	32	36	38	54	67	25
12-Jan-17	42	26	28	40	48	38	40	54	26	25
19-Jan-17	58	66	30	40	22	36	40	32	92	25
26-Jan-17	212	46	14	22	32	30	36	46	76	25
02-Feb-17	98	108	26	32	30	36	26	40	186	25
09-Feb-17	56	38	12	22	14	34	14	38	500	25
16-Feb-17	52	40	24	18	18	22	20	34	73	25
23-Feb-17	48	120	8	22	18	36	18	34	50	25
02-Mar-17	58	26	27	26	24	12	26	23	41	25
09-Mar-17	59	24	12	8	14	17	16	12	20	25
16-Mar-17	90	84	18	32	26	34	46	42	66	25
23-Mar-17	76	42	24	18	8	16	24	6	52	25
30-Mar-17	109	69	12	17	34	40	25	48	20	25
06-Apr-17	232	32	14	21	28	31	26	44	39	25
13-Apr-17	324	110	26	22	24	23	37	46	42	25
20-Apr-17	332	152	36	34	38	42	54	46	118	25
27-Apr-17	144	52	30	12	40	42	36	62	39	25

Ammonia (NH₃-N)

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1	WOC
09-Aug-16	38.33	35.67	34.08	33.42	35.13	35.84	35.49	36.01	35.44	3
18-Aug-16	48.63	37.51	37.61	37.91	36.55	36.08	36.6	37.49	38.82	3
23-Aug-16	17.82	24.91	23.83	22.63	25.05	24.47	24.97	24.87	20.01	3
01-Sep-16	39.66	37.35	37.12	36.54	35.77	37.87	36.55	38.65	37.99	3
06-Sep-16	15.67	17.43	18.73	16.61	19.85	19.42	19.79	19.72	16.52	3
15-Sep-16	19.02	22.96	24.95	21.82	24.21	23.92	24.31	24.67	21.67	3
06-Oct-16		26.62	18.39	12.3	6.38	2.7	42.8	40.95	36.42	3
12-Oct-16	40.89	37.8	38.27	36.67	41.76	41.31	42.8	40.95	39.52	3
19-Oct-16	26.45	25.69	25.75	26.18	16.02	12.94	16.14	14.76	26.92	3
26-Oct-16	48.36	35.06	33.75	32.83	37.03	35.02	37.21	35.04	44.53	3
02-Nov-16	47.76	38.46	36.36	35.12	40.93	38.31	40.9	37.7	46.17	3
10-Nov-16	16.59	14.76	12.38	13.13	16.12	16.83	16.25	17.2	15.05	3
17-Nov-16	22.01	21.95	21.16	21.02	26.5	25.71	26.03	25.57	22.52	3
24-Nov-16	22.53	29.28	29.98	28.98	36.61	35.06	36.08	34.1	22.81	3
01-Dec-16	26.64	32.79	35.78	33.92	36.11	36.45	37.38	37.18	26.45	3
08-Dec-16	31.46	36.19	33.84	33.48	33.54	34.04	33.7	32.33	32.28	3
15-Dec-16	28.35	26.36	25.43	25.73	30.06	26.12	28.33	27.18	21.83	3
05-Jan-17	35.57	33.4	33.62	33.34	32.99	33.35	33.75	33.28	31.5	3
12-Jan-17	26.11	26.66	26.94	26.82	28.43	28.13	28.27	27.28	23.26	3
19-Jan-17	29.4	29.57	29.83	29.69	26.88	29.61	26.59	24.67	23.78	3
26-Jan-17	28.32	34.45	35.2	35.29	33.24	35.62	33.04	29.31	28.49	3
02-Feb-17	20.99	0.24	16.11	14.96	13.85	19.24	15.49	17.02	19.98	3
09-Feb-17	21.87	21.67	19.66	18.78	21.03	23.68	18.34	23.19	25.55	3
16-Feb-17	27.18	19.57	37.15	35.63	25.72	29.78	38.9	27	41.23	3
23-Feb-17	32.72	38.12	38.44	37.68	26.34	30.52	41.64	27.14	44.54	3
02-Mar-17	21.03	22.8	24.45	26.43	26.57	10.68	25.23	16.11	20.98	3
09-Mar-17	20.29	17.12	18.03	18.89	22.69	17.42	17.11	10.58	13.9	3
16-Mar-17	19.98	35.24	33.77	33.73	26.26	26.13	34.74	23.58	44.85	3
23-Mar-17	18.02	17.87	17.51	17.55	15.44	6.82	18.44	12.53	17.47	3
30-Mar-17	19.49	25.76	29.12	27.6	29.47	29.77	27.39	28.42	19.25	3
06-Apr-17	21.89	26.32	27.08	28.74	30.45	30.38	31.13	29.7	20.39	3
13-Apr-17	25.96	31.46	31.06	33.24	33.21	32.89	32.94	31.17	19.51	3
20-Apr-17	31.51	37.71	37.21	37.51	37.08	36.81	37.05	34.81	32.02	3
27-Apr-17	35.42	34.44	34.95	37.7	37	36.79	37.16	36.08	27.38	3

Chemical Oxygen Demand (COD)

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	540	329	317	743	309	291	330	360	705
18-Aug-16		1460	339	342	251	263	285	303	377.6
23-Aug-16	205	211	222	191	211	221	225	251	195
01-Sep-16	335	2190	276	290	215	219	235	265	109
06-Sep-16	146	37.6	136	158	129	183	187	178	148
15-Sep-16	275	216	245	97.8	117	132	122	127	248
22-Sep-16	430	173	197	167	243	223	247	247	187
29-Sep-16	430	200	179	201	231	248	256	266	238
06-Oct-16		124	84.3	78.3	77.6	68.5	240	273	290
12-Oct-16	280	205	224	197	205	197	240	273	253
19-Oct-16	200	137	133	137	125	102	139	131	184
26-Oct-16	318	193	213	200	236	256	259	296	273
02-Nov-16	314	209	315	221	238	253	282	300	297
10-Nov-16	174	87.8	91.1	81.6	150	117	154	144	132
17-Nov-16	190	147	165	150	199	208	210	246	2924
24-Nov-16	236	203	235	224	302	328	321	380	445
01-Dec-16	315	227	261	246	276	297	282	350	255
08-Dec-16	333	225	252	241	251	230	256	280	294
15-Dec-16	263	181	196	186	212	197	213	235	222
05-Jan-17	295	230	256	255	229	234	237	289	294
12-Jan-17	289	203	227	227	259	256	263	293	227
19-Jan-17	299	207	232	233	239	249	236	221	279
26-Jan-17	909	220	347	295	674	308	294	796	423
02-Feb-17	277	138	103	115	122	167	104	162	168
09-Feb-17	245	144	132	132	176	224	132	248	596
16-Feb-17	237	91.6	204	194	165	255	228	218	292
23-Feb-17	301	224	198	202	174	239	239	237	37
02-Mar-17	207	154	149	154	154	103	168	129	198
09-Mar-17	172	125	124	123	137	117	125	96.2	148
16-Mar-17	249	247	208	205	197	235	215	216	321
23-Mar-17	161	95	79.8	83	74.3	47	83.4	58.9	136
30-Mar-17	270	205	192	195	247	267	452	297	216
06-Apr-17	511	177	180	194	229	253	272	297	222
13-Apr-17	434	277	209	224	274	293	285	334	214
20-Apr-17	595	294	252	256	290	330	346	368	397
27-Apr-17	492	230	237	206	254	287	299	306	222

pH

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	8.2	7.3	7.3	7.4	7.4	7.4	7.4	7.3	7.1
18-Aug-16		7.2	7.2	7.3	7.3	7.3	7.2	7.2	7.1
23-Aug-16	7	7.2	7.1	7.3	7.2	7.2	7.2	7.2	7.1
01-Sep-16	8.3	7.2	7.3	7.4	7.2	7.3	7.3	7.2	7.1
06-Sep-16	7	7.3	7.2	7.4	7	7.2	7.1	7.1	7.2
15-Sep-16	7.3	7.3	7.2	7.3	7.1	7.2	7.1	7.1	7.2
22-Sep-16	7.8	7.4	7.2	7.4	7.2	7.3	7.3	7.2	7.3
29-Sep-16	8	7.3	7.3	7.4	7.2	7.3	7.2	7.3	7.2
06-Oct-16		7.5	7.4	7	7.1	7.2			7.22
12-Oct-16	7	7.3	7.3	7.3	7.3	7.5	7.3	7.3	7.2
01-Dec-16	7.1	7.2	7.1	7.2	7.2	7.2	7.2	7.2	7.2
08-Dec-16	7.3	7.1	7.2	7.2	7.2	7.3	7.2	7.3	7.3
15-Dec-16	7.5	7.3	7.3	7.3	7.3	7.3	7.4	7.4	7.4
05-Jan-17	7.5	7.3	7.3	7.3	7.3	7.4	7.4	7.4	7.4
12-Jan-17	7.3	7.3	7.3	7.3	7.2	7.3	7.3	7.3	7.3
19-Jan-17	7.3	7.2	7.2	7.3	7.3	7.4	7.3	7.3	7.3
26-Jan-17	7.3	7.2	7.2	7.3	7.3	7.4	7.4	7.4	7.3
02-Feb-17	7.2	7.3	7.3	7.3	7.2	7.3	7.4	7.3	7.4

NB: pH analysis was not carried out for a period of 6 weeks between October and December.

Nitrates

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	0.49	0.47	0.48	0.52	0.48	0.48	0.48	0.49	0.51
18-Aug-16		0.17	0.16	0.16	0.16	0.15	0.14	0.14	0.17
23-Aug-16	0.05	2.71	0.32	0.23	0.45	0.48	0.46	0.89	0.05
01-Sep-16	0.05	0.16	0.15	0.15	0.15	0.16	0.15	0.15	0.16
06-Sep-16	0.5	0.47	0.48	0.47	0.49	0.49	0.48	0.48	0.48
15-Sep-16	1.13	0.42	0.42	0.41	0.41	0.42	0.42	0.43	0.42
06-Oct-16		0.29	0.31	0.31	0.33	0.4	0.3		0.29
12-Oct-16	0.31	0.3	0.29	0.29	0.29	0.29	0.49	0.29	0.47
19-Oct-16		0.39	0.39	0.39	0.38	0.39	0.39	0.4	0.38
26-Oct-16	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
02-Nov-16	0.35	0.36	0.36	0.37	0.36	0.37	0.35	0.37	0.38
10-Nov-16	1.19	2.45	0.88	0.2	0.22	0.22	0.23	0.24	0.24
17-Nov-16	0.49	0.48	0.48	0.48	0.46	0.5	0.47	0.47	0.48
24-Nov-16	0.42	0.41	0.42	0.42	0.37	0.41	0.42	0.42	0.42
01-Dec-16	0.32	0.35	0.35	0.35	0.37	0.35	0.34	0.34	0.3
08-Dec-16	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
15-Dec-16	1.26	0.49	0.34	0.33	0.34	0.34	0.34	0.32	0.31

**Where a value of 0.05 is recorded, a lab analysis of <0.1 was determined and an average calculated*

Nitrites

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	0.06	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
18-Aug-16		0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
23-Aug-16	0.005	0.03	0.005	0.005	0.005	0.005	0.01	0.01	0.005
01-Sep-16	0.08	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
06-Sep-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
15-Sep-16	0.03	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
06-Oct-16		0.005	0.005	0.005	0.005	0.03			0.005
12-Oct-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
19-Oct-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
26-Oct-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
02-Nov-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
10-Nov-16	0.06	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.02
17-Nov-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
24-Nov-16	0.005	0.005	0.005	0.005	0.02	0.005	0.005	0.005	0.005
01-Dec-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
08-Dec-16	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
15-Dec-16	0.03	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005

**Where a value of 0.005 is recorded, a lab analysis of <0.01 was determined and an average calculated*

Total Nitrogen

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	0.55	0.45	0.46	0.5	0.46	0.46	0.45	0.46	0.47
18-Aug-16		0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
23-Aug-16	0.12	2.74	0.31	0.12	0.45	0.48	0.47	0.9	0.12
01-Sep-16	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
06-Sep-16	0.47	0.45	0.46	0.45	0.47	0.47	0.46	0.45	0.46
15-Sep-16	1.16	0.4	0.4	0.4	0.39	0.4	0.4	0.41	0.4
06-Oct-16		0.26	0.29	0.28	0.3	0.43			0.26
12-Oct-16	0.3	0.3	0.29	0.29	0.29	0.29	0.3	0.29	0.46
19-Oct-16	0.39	0.37	0.37	0.37	0.36	0.37	0.36	0.38	0.36
26-Oct-16	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
02-Nov-16	0.32	0.33	0.33	0.34	0.33	0.34	0.32	0.34	0.35
10-Nov-16	1.25	2.44	0.87	0.12	0.12	0.12	0.12	0.12	0.26
17-Nov-16	0.45	0.45	0.44	0.44	0.42	0.47	0.43	0.43	0.44
24-Nov-16	0.4	0.39	0.4	0.4	0.39	0.39	0.4	0.39	0.4
01-Dec-16	0.29	0.32	0.32	0.32	0.34	0.32	0.31	0.32	0.3
08-Dec-16	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
15-Dec-16	1.29	0.48	0.33	0.32	0.32	0.33	0.32	0.31	0.31

**Where a value of 0.12 is recorded, a lab analysis of <0.24 was determined and an average calculated*

Phosphorus

Date	Inlet	T1	T2	T3	T4	T5	T6	T7	H1
09-Aug-16	4.9	4.97	4.96	4.94	4.98	4.99	4.95	5.04	4.68
18-Aug-16		5.33	4.88	5.2	4.98	4.91	4.86	4.92	5.07
23-Aug-16	2.96	3.38	3.64	3.25	3.71	3.67	3.71	3.83	3.1
01-Sep-16	5.4	5.62	4.99	5.14	4.74	5.01	4.94	4.67	5.18
06-Sep-16	2.53	2.84	3.11	2.69	3.14	3.22	3.13	3.16	2.6
15-Sep-16	3.54	3.85	4.06	3.64	3.71	3.76	3.77	3.79	3.53
06-Oct-16		3.61	2.16	1.91	1.15	0.71			5.48
12-Oct-16	5.68	5.5	5.6	4.97	5.84	5.76	5.99	5.69	5.09
19-Oct-16	3.51	3.34	3.32	3.39	2.53	2.16	2.56	2.31	3.51
26-Oct-16	6.34	5.05	4.92	4.93	4.77	4.98	4.74	5.08	6.13
02-Nov-16	6.19	5.48	5.36	5.15	5.55	5.42	5.74	5.45	6.05
10-Nov-16	2.55	2.1	1.94	1.9	2.46	2.57	2.55	2.66	2.08
17-Nov-16	3.11	3.43	3.39	3.34	3.78	3.9	3.76	3.9	3.48
24-Nov-16	3.92	4.77	4.76	4.78	4.33	4.76	4.46	5.32	3.72
01-Dec-16	4.39	4.78	4.5	4.64	4.08	4.47	4.68	4.63	4.29
08-Dec-16	4.69	4.94	4.49	4.65	4.42	4.78	4.76	4.77	4.79
15-Dec-16	4.35	3.91	3.81	3.86	4.21	3.84	4.08	3.97	3.47

H1 Water Depth V Treatment

Date	Water Depth	BOD	SS	NH ₃ -N	COD
09-Aug-16	-200	352	792	35.44	705
18-Aug-16	-200	184.8	50	38.82	377.6
23-Aug-16	-200	142	20	20.01	195
01-Sep-16	-200	226	226	37.99	109
06-Sep-16	-100	124	15	16.52	148
15-Sep-16	-100	217	20	21.67	248
22-Sep-16	-100	76.3	29		187
29-Sep-16	-100	121	26		238
06-Oct-16	0	165.6	26	36.42	290
12-Oct-16	0	172	24	39.52	253
19-Oct-16	0	114	24	26.92	184
26-Oct-16	0	110	36	44.53	273
02-Nov-16	-200	145	36	46.17	297
10-Nov-16	-200	109.9	132	15.05	132
17-Nov-16	-200	8.32	985	22.52	2924
24-Nov-16	-200	154	368	22.81	445
01-Dec-16	-100	123.2	42	26.45	255
08-Dec-16	-100	143	50	32.28	294
15-Dec-16	-100	119.2	42	21.83	222
05-Jan-17	0	148.4	67	31.5	294
12-Jan-17	0	105	26	23.26	227
19-Jan-17	0	117	92	23.78	279
26-Jan-17	0	164	76	28.49	423
02-Feb-17	-200	87.5	186	19.98	168
09-Feb-17	-200	194	500	25.55	596
16-Feb-17	-200	135.1	73	41.23	292
23-Feb-17	-200	135	50	44.54	37
02-Mar-17	-100	112	41	20.98	198
09-Mar-17	-100	74.9	20	13.9	148
16-Mar-17	-100	148	66	44.85	321
23-Mar-17	-100	50.4	52	17.47	136
30-Mar-17	0	115	20	19.25	216
06-Apr-17	0	100.8	39	20.39	222
13-Apr-17	0	125	42	19.51	214
20-Apr-17	0	179.2	118	32.02	397
27-Apr-17	0	114	39	27.38	222