



SYED SHUJA UL HASSAN

INVESTIGATING THE HYDRAULIC PERFORMANCE OF FULL-
SCALE TREATMENT WETLANDS USING ELECTRICAL
RESISTIVITY TOMOGRAPHY

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
CRANFIELD WATER SCIENCE INSTITUTE

MSc BY RESEARCH
Academic Year: 2021 - 2023

Supervisor: Dr. Yadira Bajón-Fernández
Associate Supervisor: Dr. Tao Lyu
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EXECUTIVE SUMMARY

Horizontal subsurface flow constructed wetlands (HSFCWs) have been widely used for tertiary treatment of wastewater in the United Kingdom (UK). One of the main objectives for UK's water industry is achieving a reduction in maintenance costs of HSFCWs by reducing frequency and cost of clogging remedial measures. However, inability of conventional clogging assessment methods to provide reliable subsurface visualisation of the HSFCWs limits understanding of clogging profiles across treatment units, hindering proactive maintenance and remedial interventions. Without trustworthy information about subsurface conditions of HSFCWs, clogging remedial measures cannot be optimised to provide targeted, proactive, and cost-effective maintenance. In this study, electric resistivity tomography (ERT) has been applied to identify its effectiveness to provide reliable visualisation of the subsurface conditions of HSFCWs.

On this project, two HSFCWs with different clogging levels were tested using ERT. Anomalies in subsurface distribution of water and profiles of clog matter accumulation across the HSFCWs were identified by changes in electric resistance of the media. The output was in form of cross sections showing variation in resistance across the media with different colours. The visual representation of subsurface conditions covered the full depth as well as the length of HSFCWs. The subsurface conditions identified in ERT results were in line with those observed by conventional clogging measurement methods, including substrate permeability measurement and tracer test, which provides preliminary validation of the ERT methodology.

A recently refurbished HSFCW was found to have negligible level of clogging and subsurface visualisation was depicted by consistent shades showing uniform electric resistivity values (between 20 to 300 ohm.m) across the HSFCW. Contrarily, a mature HSFCW with many years of operation and no recent remedial interventions resulted in significant colour variation across the sections, indicating uneven electric resistance across the HSFCW (between 20 to 4000 ohm.m) and the ability of the ERT methodology to infer clogging levels.

Considerably higher resistivity values and their chaotic variations across the subsurface indicated the distribution of wastewater and clog matter.

To Identify the effectiveness of ERT to visualise subsurface of wetland systems, two different ERT arrays (electrode configurations) were used: Dipole-Dipole characterised by better horizontal resolution and effective depth coverage at the ends of ERT line and Wenner Array characterised by better vertical resolution and less susceptibility to noise. Both arrays were successful in identifying variations in local clogging levels in the HSFCWs, with the Dipole-Dipole array results found to be more relatable with actual site conditions. This work has evidenced the potential of ERT to profile clogging in HSFCWs, providing a tool for implementing targeted asset maintenance and reduced operational costs. Further improvement in the ERT methodology is recommended by testing the impact of smaller probe spacing, controlled water levels in HSFCWs, and increased observations of the same systems at different operation ages.

ACKNOWLEDGEMENTS

He has let free the two bodies of flowing water, meeting together. Between them is a barrier which they do not transgress. Then which of the favours of your Lord will ye deny? - Al-Qur'an: 55 (19-21).

I can't deny the favours ALLAH has bestowed on me. My sincere gratitude and gratefulness go out to the Almighty for all that He has given me. The gratitude also goes to the educator of humankind Holy Prophet Muhammad (Peace be Upon Him), who has no educator to him but ALLAH. Execution of this research work has been a matter of immense inspiration and a strong prevailing elation for me.

I would like to express my deepest gratitude to my supervisors, Dr Yadira Bajón Fernández and Dr Tao Lyu for their excellent guidance, support, and patience over the duration of my research endeavour. The successful completion of this dissertation has only been possible due to their intense interest in my work, and continuous support and caring attitude towards me. Special gratitude also goes to Dr Gabriela Dotro for starting this project and giving me opportunity to be a part of this. I am also thankful to School of Water, Energy and Environment (SWEE), Cranfield University, for providing me the resources and supportive environment to carry out this study.

I am also grateful to Abydoz Environmental Inc. for funding this project and Severn Trent for providing access to HSFCWs. I would like to gratefully acknowledge the support of Peter Master who provided in developing methodology for the ERT. Special thanks to Chimamaka Amala for her continuous support from start of the project.

Most importantly, none of this would have been possible without the love and patience of my family. I would like to express my heartfelt gratitude to my wife and my parents. They have been a constant source of love, support, and strength all this time.

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LIST OF EQUATIONS

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LIST OF ABBREVIATIONS

CW	Constructed Wetland
ERT	Electric Resistivity Tomography
GPR	Ground Penetrating Radar
HC	Hydraulic Conductivity
HSFCW	Horizontal Subsurface Flow Constructed Wetland
IP	Induced Polarization
RBC	Rotating Biological Contactor
RMS	Root Mean Square
UK	United Kingdom

1 INTRODUCTION

Constructed wetlands (CWs), as a nature-based solution, are widely used for wastewater treatment and deliver multi-benefits, such as carbon sequestration and enhanced biodiversity (Semeraro et al., 2015). These systems are claimed to have reduced operation and maintenance needs and subsequently lower associated costs, compared to traditional wastewater treatment facilities (Zhao et al., 2020). The design of CWs combines the effects of natural processes to achieve wastewater treatment through the interaction of wastewater with vegetation, gravel, and microbial communities present in the system (David et al., 2022). Most designs of constructed wetlands involve the horizontal or vertical flow of wastewater through the subsurface of a media that is planted with wetland vegetation such as *Typha Latifolia* and *Phragmites Australis* (Parde et al., 2021). In horizontal subsurface flow constructed wetlands (HSFCWs), a shallow rectangular bed of gravel is planted with wetland vegetation, and wastewater is fed from one side which slowly passes through the bed and is collected at the other end. HSFCWs are designed to maintain a water table below the surface, creating favourable conditions for pollutant removal (Hadidi, 2021).

Long term operation of CWs can lead to clogging, a phenomenon characterized by the gradual decrease in water permeability within the wetland bed (Adrados et al., 2014). Clogging in HSFCWs is attributed to decrease in size and number of voids in the media due to accumulation of organic and inorganic solids, microbial growth, and root intrusion (Wang et al., 2021). This results in blockage in certain portions of the subsurface and creation of preferential flow paths in the media. The subsurface nature of clogging means that progressive accumulation of solids on the treating media is frequently overlooked until permeability and treatment performance, are heavily impacted.

The negative impacts of clogging in HSFCWs are well-documented in literature. Studies have shown that clogging can reduce the hydraulic conductivity of HSFCWs by up to 50%, severely impairing their ability to maintain uniform flow in the subsurface. Over flow and surface ponding, resulting from reduced water permeability, can lead to decreased treatment performance and the release of

untreated water (Tang et al., 2017). Additionally, clogging can hinder the growth and activity of beneficial microorganisms responsible for pollutant degradation, further reducing the treatment capacity of HSFCWs. Zhang et al. (2021) found that clogging decreased the abundance and diversity of microbial communities in HSFCWs, accompanied with 13%-17% decrease in filtration rate. Along with the decremental effect on treatment efficiency, clogging has also been identified as a major reason for shortened service life of CWs (Tan et al., 2022).

Remedial actions required to revert clogging and sustain treatment capacity and performance translate into increased operational costs for CWs. Clogging interventions in CWs are usually triggered according to time intervals or once operation has been compromised, with a great opportunity to implement proactive inspection strategies that can be routinely implemented to inform refurbishment needs.

The commonly used methods to evaluate clogging development in CWs are the measurement of hydraulic conductivity and tracer testing (Wang et al., 2021). Hydraulic conductivity provides an indication of the overall permeability of the media, regularly based on few test points, and assuming homogenous solids accumulation across the media depth. Tracer testing aims to define variations in water hydraulic retention time, again providing an average indication of clogging levels without any resolution on solids accumulation profiles across the media (Nivala et al., 2012). These conventional methods for clogging measurement often face limitations in accurately assessing the extent of clogging and are unable to provide visualization of subsurface conditions. Hydraulic conductivity measurements, while commonly used, are time-consuming, labour-intensive, and require multiple sampling points to capture spatial variability (Le Coustumer et al., 2012). Additionally, they provide point-specific information, which may not fully represent the overall clogging distribution within the wetland system. The heterogeneity of gravel media and clogging patterns further complicates the interpretation of hydraulic conductivity measurements (Liu et al., 2018). Tracer tests, on the other hand, do not fully capture the complex behaviour of clogging matter in the system. Tracer measurement can usually be measured at the outlet,

and it is difficult to monitor tracer passage at various points inside an operational CW. These tests provide information regarding overall water retention of the system and offer limited information about the spatial distribution of flow patterns and clog matter. Nivala et al. (2012) summarized that the tracer test results show discrepancies when compared with internal distribution of hydraulic conductivity, highlighting the limitations of this method in accurately characterizing clogging in HSFCWs.

Currently, the remediation of clogging in constructed wetlands is primarily achieved through physical interventions such as dredging or desludging. These methods involve the removal of accumulated solids and organic matter from the wetland system to restore its hydraulic treatment capacity. For HSFCWs clogged media is being reused after excavation and cleaning to reduce costs by up to 55% (Nivala et al., 2012). While these methods can provide short-term relief, they have several limitations. First, the efficiency of these remediation methods may vary depending on the composition and characteristics of the clogging material. Second, they are labour-intensive and require substantial financial resources, especially for large-scale wetlands. Moreover, these activities produce waste containing high concentration of pollutants. Alternate methods for clogging removal like resting the system, use of chemicals and earthworms, have been tested but the results show that these techniques still need further development (de Matos et al., 2018). This project recognises there is a need for improved clogging remediation methods that are more efficient, cost-effective, and environmentally friendly. The development of such methods requires a better understanding of the accumulation, dynamics, and composition of clogging materials, highlighting the importance of reliable clogging measurement techniques to inform targeted and optimized remediation strategies like partial refurbishment.

Geophysical methods have emerged as promising alternatives for clogging measurement in HSFCWs. Induced polarization (IP), for example, measures variations in electrical chargeability to assess the presence and distribution of clogging matter. Garcia-Artigas et al. (2020) conducted a study using IP in lab

scale HSFCWs and found that it successfully identified areas with high chargeability associated with clogging. However, the technique requires specialized equipment and expertise for accurate interpretation.

Ground-penetrating radar (GPR), another geophysical technique, utilizes variation in speed of electromagnetic waves through different material types to generate high-resolution subsurface images. GPR study on full scale HSFCWs found that it can effectively identify clogging layers, providing detailed information about the distribution of subsurface clogging materials (Matos et al., 2019). However, it provides difficulty in application on operational CWs as GPR encounter challenges in densely vegetated or heavily pounded areas (Nivala et al., 2012).

Among the geophysical methods, electrical resistivity tomography (ERT) has shown significant promise for clogging measurement in HSFCWs. ERT measures variation of electric resistivity across a subsurface and the results can provide information to identify distribution of materials of different density and moisture content in the subsurface (Falae et al., 2019). The measurements are carried out by using different multielectrode configurations called arrays which is mainly based on spacing and distribution of current electrodes and potential electrodes. Array to be used is chosen based on expected subsurface conditions as different electrode configurations are effective in identifying different types of subsurface resistivity variations (Liu et al., 2022). Studies have reported that clogging can result in a decrease of up to 50% in substrate apparent resistivity due to relatively higher water content of clogging matter (Liu et al., 2018) ERT can effectively identify the extent and location of clogging, providing valuable information for targeted maintenance interventions and decision-making in HSFCWs (Liu et al., 2022). Although ERT offers significant advantages, such as non-invasive and continuous monitoring capabilities, it also has its limitations. The interpretation of geophysical data can be complex and requires advanced analysis techniques to obtain accurate and reliable results. Researchers have discussed the challenges associated with the interpretation of ERT data in heterogeneous environments, highlighting the need for improved analysis methods to enhance the spatial

resolution and interpretation of ERT data in complex media (Ergaieg et al., 2021; Liu et al., 2022; Nivala et al., 2012).

A few studies have focused on ascertaining suitability of Electric Resistivity Tomography (ERT) on measuring hydraulic performance of CWs. Nevertheless, further studies are required to develop these methods to visualise the complicated subsurface phenomenon in order to acquire reliable clogging measurement results (Nivala et al., 2012). As ERT is still in development phase of its application on CWs it is important to identify effectiveness of different arrays in visualisation of subsurface clogging conditions (Liu et al., 2022). Accurate visualisation of subsurface clogging can enable operators to undertake focused clogging remediation measurements on parts of the HSFCWs instead of full refurbishment. These targeted partial refurbishments can further reduce operational and maintenance costs and increase operational age of the HSFCWs.

1.1 Aim and Objectives

This study aims to explore the effectiveness of the Electric Resistivity Tomography (ERT) method to profile clogging levels in the subsurface of operational full-scale HSFCWs, enabling the operators to carry out proactive partial refurbishment and improve lifespan of CWs. The ERT methodology was mended to be suitable for visualisation of the shallow beds of HSFCWs.

The following specific objectives were defined:

Objective 1. To obtain the 2D visualizations of the subsurface clogging profile of one mature and one recently refurbished full-scale HSFCW, using different arrays of Electric Resistivity Tomography (ERT)

Objective 2. To evaluate the ERT method through the comparison of ERT results with conventional clogging measurement methods (i.e., hydraulic conductivity and tracer testing) and comparison of clogged and recently refurbished HSFCW.

1.2 Thesis Plan

This project responds to a need of a water utility and related experiments were hence conducted on full-scale sites. The thesis comprises of two chapters. In chapter 1 the background of the project is introduced, along with a summary of related previous literature and state-of-the-art of the ERT methodology. This chapter also includes the thesis aim and objectives. Chapter 2 presents the method development for adapting the ERT methodology to HSFCWS, which are shallower than most previous applications of ERT, and the findings of the experimentation carried out on two operational HSFCWs. Both chapters have been written by Syed Shuja ul Hassan and edited by Dr. Tao Lyu and Dr. Yadira Bajón Fernández. All experimentation was carried out by Syed Shuja ul Hassan with exception of historical water quality data of the mature HSFCW, which was provided by Severn Trent who operate the site.

2 INVESTIGATING THE HYDRAULIC PERFORMANCE OF FULL-SCALE TREATMENT WETLANDS USING ELECTRIC RESISTIVITY TOMOGRAPHY

Syed Shuja ul Hassan, Tao Lyu, Gabriela Dotro, Yadira Bajón-Fernández

Abstract

Remedial measures for clogged horizontal subsurface flow constructed wetlands (HSFCWs) rely on information provided by clogging measurement techniques. However, conventional clogging measurement techniques are indirect and do not provide enough information for visualisation of subsurface clogging development. This study explored suitability of electric resistivity tomography (ERT) to visualise clogging development in full scale operational HSFCWs. ERT was carried out using Wenner array and Dipole-Dipole array, on two full scale HSFCWs, one has been in operation for 10 years without refurbishment and another has been recently refurbished. Conventional methods of visual observations, hydraulic conductivity and tracer testing were also performed to verify the ERT results. Both Wenner and Dipole-Dipole arrays effectively identified variation in subsurface resistivity across mature HSFCW. Moreover, ERT results from recently refurbished HSFCW indicated uniform subsurface resistivity. Variation in subsurface water levels ranging from 0.5 m to 0.1 m from the surface were detected by ERT across mature HSFCW, while uniform subsurface water level 0.1 m below the surface was measured for recently refurbished HSFCW. These values coincided with the physical measurements taken on the field. Further development and optimisation of ERT methodology for subsurface visualisation of HSFCWs can provide operators with reliable non-intrusive clogging monitoring tool. This can provide information required for targeted partial refurbishment of HSFCWs and make HSFCW operations more sustainable by avoiding untreated discharge, costly full refurbishments and unpredictable operational conditions.

Keywords: Clogging, constructed wetlands, hydraulic conductivity, nature-based solution, refurbishment, wastewater treatment.

2.1 Introduction

Horizontal subsurface flow constructed wetlands (HSFCWs), as a nature-based solution, have been widely used to treat various types of wastewaters and provide multi-benefits, such as carbon sequestration and enhanced biodiversity (Ingrao et al., 2020). HSFCWs involves a multifaceted interactive system comprising of plants, gravel media and microbes that work together to remove pollutants from wastewater (Du et al., 2016; Vymazal & Kröpfelová, 2009). By keeping the water level below the surface, HSFCWs can also prevent the formation of odour and the breeding of mosquitos (Foladori et al., 2014; Herrera-Melián et al., 2020). However, the phenomenon of clogging can pose a threat to these advantages, as organic and inorganic solids accumulate over time on the wetland media and impair the system's effectiveness (Knowles et al., 2011).

Clogging has been recognised as one of the most significant operational challenges in constructed wetlands (CWs) (Pedescoll et al., 2011; Wang et al., 2021), as it can result in reduced treatment performance, a shortened operational lifespan, and the deleterious aesthetic value as well as environmental issues due to surface water ponding (Adrados et al., 2014). Clogging in constructed wetlands has been shown to have a negative impact on subsurface microorganisms, leading to a significant reduction in biodegradation rates by up to 60% (Hua et al., 2018) and compromising the overall treatment performance. Furthermore, clogging can lead to a decrease of up to 50% in pollutant removal rates, further compromising the treatment effectiveness of the system (Li et al., 2021). With progression of clogging in a CW, preferential flow paths may develop both over and under the surface of the wetlands, which may cause short-circuiting and result in water flowing on the surface and untreated water discharges (Botes et al., 2018; de Matos et al., 2018). The reduced contact time between pollutant and microorganisms can further affect the pollutant removal performance. Moreover, the occurrence of surface ponding in clogged CWs can lead to various operational risks and environmental problems. Excessive surface ponding can impede the proper flow of wastewater, resulting in reduced hydraulic capacity and further compromised treatment efficiency. Studies have shown that clogging-induced surface ponding can cause a significant decrease in hydraulic

conductivity, with reductions of up to 50% reported in some cases (Tang et al., 2017). This reduction in hydraulic conductivity directly impacts the ability of the wetland to effectively treat wastewater and can lead to stagnant conditions, increased odours, and release of untreated or partially treated effluent into the surrounding environment (Lavrnić et al., 2018). Consequently, the reduction in permeability caused by clogging has a significant impact on the intended lifespan of the wetlands, with potential to reduce the operational time between refurbishments by a factor of ten (Keng et al., 2021; Nivala et al., 2012). Therefore, it is crucial to continuously monitor clogging development and implement preventive measures to restore clogged areas and ensure reliable operation of CWs.

Detecting and monitoring clogging can be challenging, as it occurs below the surface and may not be observable until it reaches a critical level that causes surface flow (Nivala & Rousseau, 2009). The commonly used methods to evaluate clogging in CWs are the measurement of hydraulic conductivity and tracer testing (Wang et al., 2021). However, both approaches have limitations. Hydraulic conductivity measurement is an invasive technique that only provides local values at testing points and can be influenced by factors such as the condition of the surface media and the presence of rhizomes (Knowles et al., 2011; Matos et al., 2017). Tracer testing provides an overview of the hydrodynamic conditions in the system and its results may be affected by preferential flow paths developed in a clogged system (Matos et al., 2019). Moreover, these methods do not allow for reliable visualisation of subsurface conditions that would inform intervention strategies needed to sustain operation (Aiello et al., 2016; de Matos et al., 2018; Knowles et al., 2011). Therefore, alternative, or complementary methods that can provide more accurate and continuous monitoring of clogging in CWs are needed.

Limitations in the monitoring of clogging may be overcome by using geophysical techniques, which offer a promising solution by utilising electric and electromagnetic properties of the porous medium. These techniques have already been applied to identify soil-root interaction during deficit irrigation,

subsurface freshwater availability, and soil organic matter content (Greggio et al., 2018; Turki et al., 2019; Vanella et al., 2018). One commonly used geophysical method is electrical resistivity tomography (ERT), which provides non-destructive visualisation of subsurface conditions by measuring underground resistivity. ERT has been applied to large-scale soil electric resistivity surveys (Carrière et al., 2020; Falae et al., 2019). These studies were carried out in areas with conditions similar to CWs, where water interacts with porous media and vegetation. By measuring vertical profiles of variation in electric resistivity across shallow wetland beds, ERT can identify spatial distribution of clogging matter across HSFCWs. Therefore, successful integration of ERT monitoring into HSFCW operation and maintenance has a great potential to induce more focused and cost-effective refurbishment strategies, increased treatment efficiency, and reduced risk of unanticipated malfunctions.

Recent research has demonstrated the utility of ERT in the visualization of clogging matter distribution based on electromagnetic properties (Ergaieg et al., 2021; Garcia-Artigas et al., 2021; Matos et al., 2019). As clogging matter is typically 90% water by volume, higher water content corresponds to lower apparent resistivity of the wetland substrate. Thus, the substrate apparent resistivity exhibits a negative correlation with the volume fraction of clogging matter, providing a promising method for assessing the degree of clogging (Liu et al., 2018). Recent research has shown that ERT can be effective in monitoring of clogging development in CWs (Ergaieg et al., 2021; Liu et al., 2022; Marzo et al., 2018). Marzo et al. (2018) compared ERT values for HSFCW before and after clogging intervention and identified a general decreasing trend in substrate electrical resistivity with the removal of clogging matter. Nevertheless, there is still a need for validation of the ERT technique through comparison with traditional hydraulic conductivity measurement and tracer testing. Moreover, improvements in the data analysis of ERT data are necessary to obtain better spatial resolution.

This study aimed to compare and validate the effectiveness of ERT arrays in visualizing substrate clogging levels in full-scale HSFCWs. To identify the effectiveness of subsurface visualisation and compare spatial resolution, two

different array configurations for ERT electrodes (Dipole-Dipole Array and Wenner Array) were applied on a mature HSFCW. Conventional clogging measurement methods were also applied for verification of the ERT results. In addition, the aforementioned ERT techniques were also applied on a recently refurbished HSFCW to compare performance of ERT in clogged and unclogged HSFCWs. The main aim of this study was to investigate the effectiveness of ERT arrays to visualize substrate clogging levels of full-scale HSFCWs in operation. This will provide a reliable clogging monitoring mechanism that can enable cost effective clogging remedial measures and increase service life of CWs.

2.2 MATERIALS AND METHODS

2.2.1 The mature Horizontal Subsurface Flow Constructed Wetland

A mature HSFCW showing signs of clogging after over 10 years' operation was tested in this study. It was situated in Worcestershire, England, and was one of two HSFCWs operating in parallel for tertiary treatment of sewage water. The influent passed through an initial screening, settlement tanks and rotating biological contactor (RBC) before reaching the HSFCWs.

The HSFCW tested had a surface area of 300 m² (12 × 30 m) and was filled with gravel (grain diameter of 8–12 mm) to a depth of about 0.60 m. *Phragmites australis*, commonly known as reed, was planted on the surface (Figure 2-1 a). The facility treats an average flow rate of 222 m³ day⁻¹ with secondary treated sewage equally distributed between the two HSFCWs operating in parallel. The HSFCW has been in operation for over 10 years without any refurbishment, recently starting to show signs of subsurface clogging such as surface water ponding, uneven vegetation distribution and preferential water flow paths. During the fieldwork, the outlet pipe of the HSFCW bed was positioned approximately 10 cm from the bottom, which was significantly lower than the company's guidance of maintaining a 50 cm water level in the bed. Since the site manager did not disclose the reason for this choice, it is unclear whether it was a short/mid-term special operational requirement or an intentional acceleration of the gradient for the water to flow through the clogged subsurface to achieve statutory effluent standards. The effect of clogging on treatment performance can be observed in

historical water quality data (2017-2022) of the effluent, which evidences a significant increase in total suspended solids and slight increase in total oxidised nitrogen (Figure 2-1 b).

(a)



(b)

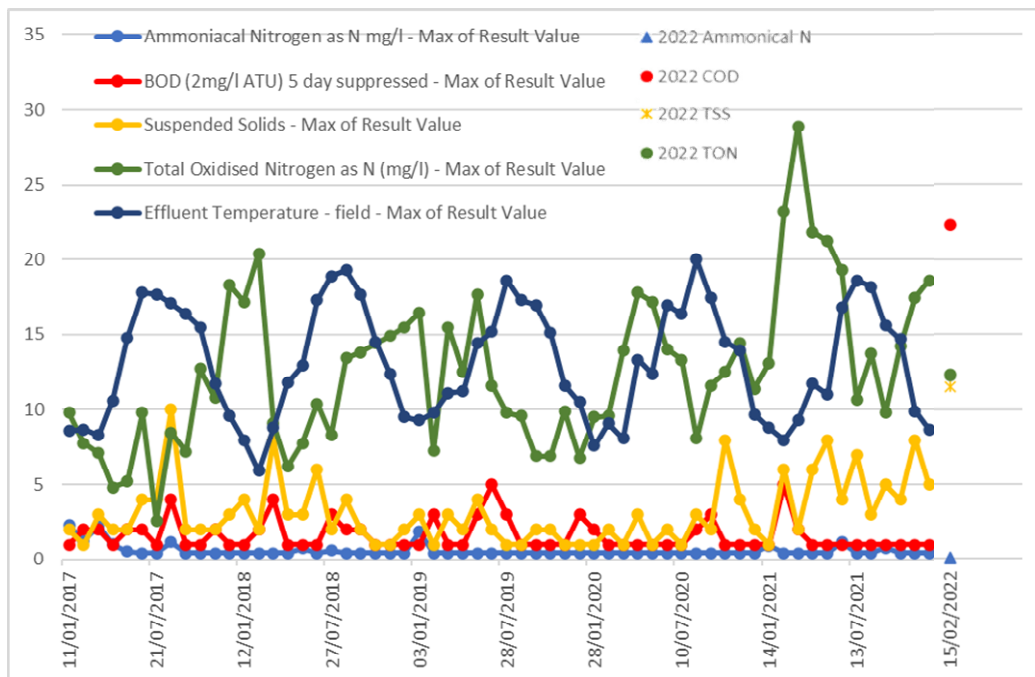


Figure 2-1 (a) HSFCW in operation and (b) historical water quality data of the HSFCW

2.2.2 Assessment of Clogging in the HSFCW System

Four lines across the HSFCW were selected to perform tests at overlapping locations (Figure 2-2). Lines A-A, B-B and C-C were selected across the HSFCW

along the direction of flow while one test of ERT was also conducted in a line perpendicular to the flow direction, across line D-D. Nine different locations across the HSFCW were designated to carry out measurements of sludge depth, water depth and hydraulic conductivity (Figure 2-2). These 9 locations overlapped across the ERT lines as, so that the results could be compared.

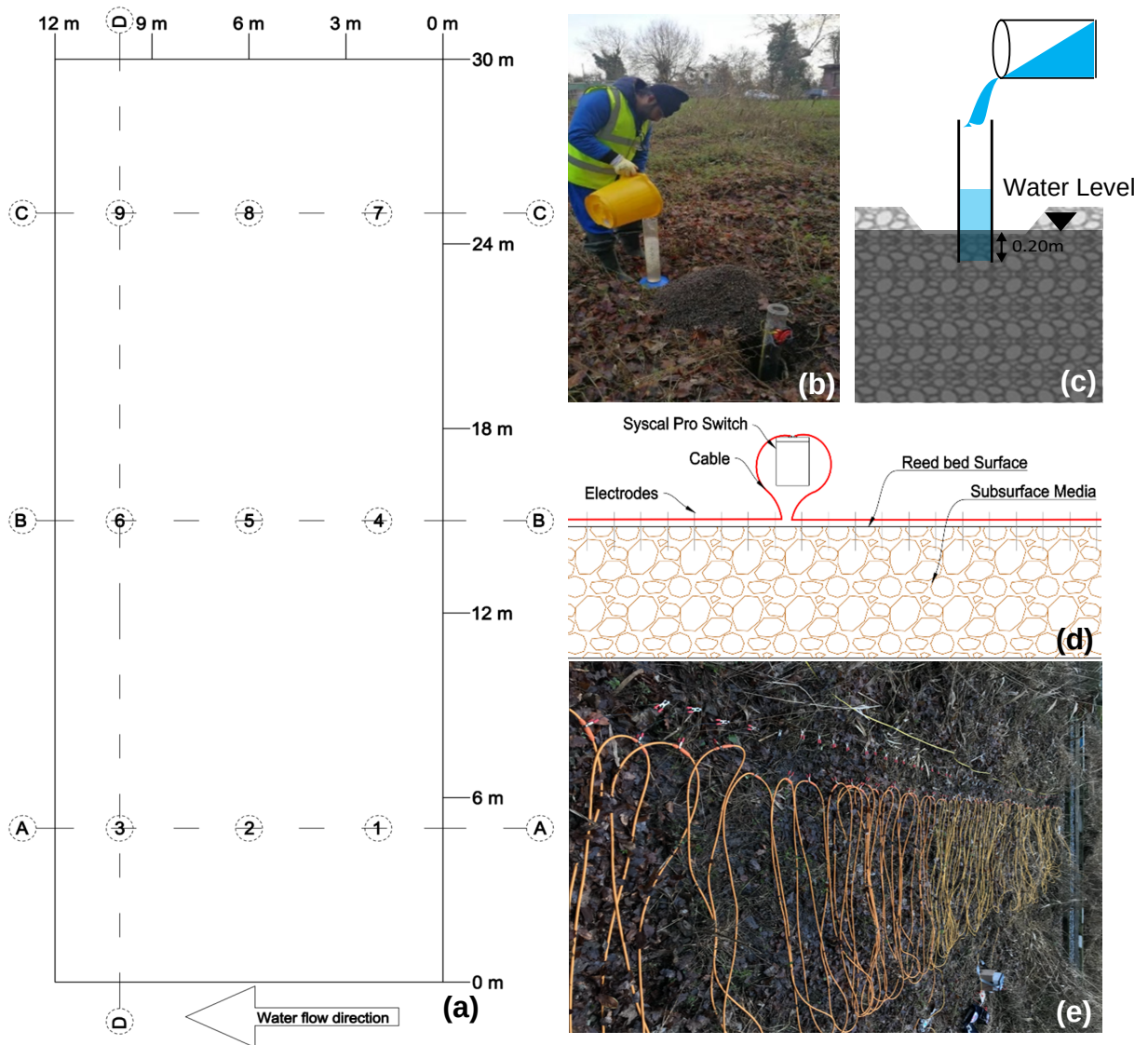


Figure 2-2 (a) Testing locations for ERT, visual inspection and hydraulic conductivity testing across the HSFCW, (b) hydraulic conductivity testing, (c) schematic diagram of HC test, (d) schematic diagram of ERT test and (e) ERT setup.

2.2.2.1 Visual Observations and Surface Condition Measurement

To measure the sludge distribution, depth of sludge and water levels across the HSFCW, visual inspections and measurements were carried out. Surface conditions including presence of plants, water ponding, and water streams were also identified and the covered areas measured. Surface sludge was removed by digging until the media was exposed and the sludge height was measured by tape measurement. Gravel media of the HSFCW was further dug out until the water level was exposed and the water level depth was recorded. Variations on surface condition were mapped to show distribution of plants, surface ponding and water streams across the HSFCW. Sludge thickness and water levels were plotted with reference to the HSFCW depth profiles along the testing lines to compare with the corresponding profiles obtained by ERT arrays.

2.2.2.2 Hydraulic Conductivity

The falling-head method was selected to determine hydraulic conductivity at saturation (K_s , $m\ d^{-1}$) (Pedescoll et al., 2009). Nine measurement points across the HSFCW arranged in 3 rows were selected, overlapping with ERT measurement lines. Sludge and granular medium were dug until the water table was reached (Figure 2-2 b & c). A cylindrical plexiglass tube with a 0.7 m internal diameter and a 1.5 m length was used for hydraulic conductivity measurements, inserting it into the medium to a depth of about 0.25 m. The tube was filled with clean water in pulse mode and the decrease of the water height was monitored until it reached the HSFCW water level (Figure 2-2 b & c).

Hydraulic conductivity at saturation (K_s , ms^{-1}) was calculated according to equation (2-1) (NAVFAC, 1986), which was obtained by combining the mass conservation principle with Darcy's law.

$$K_s = \frac{2\pi R + 11L}{11(t_2 - t_1)} \times \ln \frac{H_1}{H_2} \quad (2-1)$$

Where R is the radius of the tube (m), L is the submerged length of the tube (m), t is time (s), and H_1 and H_2 are the water levels (m) in the plexiglass tube at times t_1 and t_2 (s), respectively.

The experiment was repeated three times on each location and an average value of K_s for each of the 9 locations was calculated.

2.2.2.3 Tracer Testing

Tracer testing was performed by using Rhodamine WT as the tracer and a Cyclops sensor connected with a DataBank™ datalogger (Turner Designs, USA) was used to measure its concentration. A 1 ppm solution of Rhodamine was injected in the inlet of the system and its concentration was recorded with the sensor before moving this to the outlet point of the wetland, where the tracer concentration was monitored at a rate of 3 readings per second.

2.2.2.4 Electric Resistivity Tomography

The ERT involves measurement of variations in electric resistivity to detect subsurface materials. In this method a set of electrodes transmit electric current into the surface and another set of electrode measure amount of transmitted current. The difference in injected and observed current indicate the electric resistivity of the medium. ERT methods vary according to the configuration of electrodes used to inject current in the surface and electrodes used to measure residual current (Rosa et al., 2022). These configurations are known as arrays. In this study, electric resistivity values were measured with Dipole-Dipole array as well as Wenner array. These two arrays were preferred because of their better data collection performance in shallow depths more quickly (Moreira et al., 2016; Rosa et al., 2022). Besides, the Dipole–Dipole array is effective in identification of vertical structures, while Wenner array performs better to identify the horizontal variations (Neyamadpour et al., 2010).

The equipment used was Syscal Pro Switch 10-Channel system (IRIS Instrument, France), which was connected to the wetland surface by inserting electrodes in the surface of the HSFCW along a line with predetermined spacing (Figure 2-2 a). Array selection and electrode information was input in the switch to pre-program data collection sequences using Electre Pro Software (IRIS Instrument, France) (Figure 2-3). An electrode spacing of 0.2 m was chosen to spread an evenly spaced grid of 72 electrodes across the 15 m HSFCW (Figure 2-3 b). Appropriate array, along with suitable measurement depth levels were

chosen to ensure that the sequence will collect data up to or more than 0.6 m which was the depth of the HSFCW. The software allows to visualise the expected subsurface data collection grid to ensure that the sequence is appropriate for required depth (Figure 2-3 c). Later, all the data collection sequences were uploaded to the apparatus. Electrodes were inserted along the CW surface and were connected to the apparatus with help of cables. The connections between electrodes, cables, switch and the surface were tested by carrying out a resistivity check, and subsequently the data collection sequence relevant to the selected array was used to collect the electric resistivity data. The method was repeated on three different lines across the HSFCW from inlet to outlet direction and one line from left to right of the read bed (Figure 2-2 a).

The Dipole-Dipole and Wenner arrays were utilised to acquire electrical resistance data from the same experimental electrode setup. The acquired data was further processed using data checking and resistivity inversion programs (Res2dinv, AGS, Denmark) to generate effective apparent resistivity data at different positions across the detection sections. A user-defined contour increase factor of 1.5 along with a minimum contour value of 10 ohm.m was applied to achieve the maximum observed contour value of 4378.9 ohm.m, ensuring consistent scaling across all profiles. Caution was taken during data filtering to retain genuine extreme value observations that could be erroneously marked as outliers by automatic software routines. The inversion processes were carried out while maintaining root mean square (RMS) errors below 5%. For inversions with RMS greater than 5%, the data was reprocessed using histograms and scatter plots in RES2dinv to identify and filter software-detected outliers. Additionally, 2D visualizations of subsurface profiles for the HSFCWs were obtained through 2D inversions in Res2dinv. The 2D profiles exhibit coloured contours denoting zones of equal electric resistivity, with the software permitting the use of 17 colours for contour representation based on a user-defined contour factor and spanning between minimum and maximum resistivity values.

(a)

Creation Configuration View Graph View Sheet

Type of measurement
☒ Line (X location)
☐ Surface (X,Y location)
☐ Borehole (X,Z location)

Electrode location (m)
X grid spacing : 0.2 X grid offset : 0 X grid size : 72 ☐ Automatic grid
☒ Manual grid

Next >> Previous << Create grid

y\X (m)	0.00	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00	4.20	4.40	4.60
0.00	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

(b)

Creation Configuration View Graph View Sheet

Automatic creation > Comment :

Syscal parameters
Sequence name in Syscal : 72DD

Array
El. Array : dipole-dipole

Timing
☒ Rho ☐ Rho and IP
Time (ms) : 250 ms

Quality control
Q max (%) : 6
Stack min : 3
Stack max : 6

Voltage requested
☒ Vp : Save energy
☐ Vab :
Vab Maximum : 400

Maximum number of channels : 1

Grid of the depth levels Automatic grid filling

Spacing	Level	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43		
1 x a	4	●	●	●	●																																									
2 x a	4					●	●	●	●	●																																				
3 x a	4										●	●	●	●	●																															
4 x a	4															●	●	●	●	●																										
5 x a																																														
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7 x a																																														
8 x a																																														
9 x a																																														

(c)

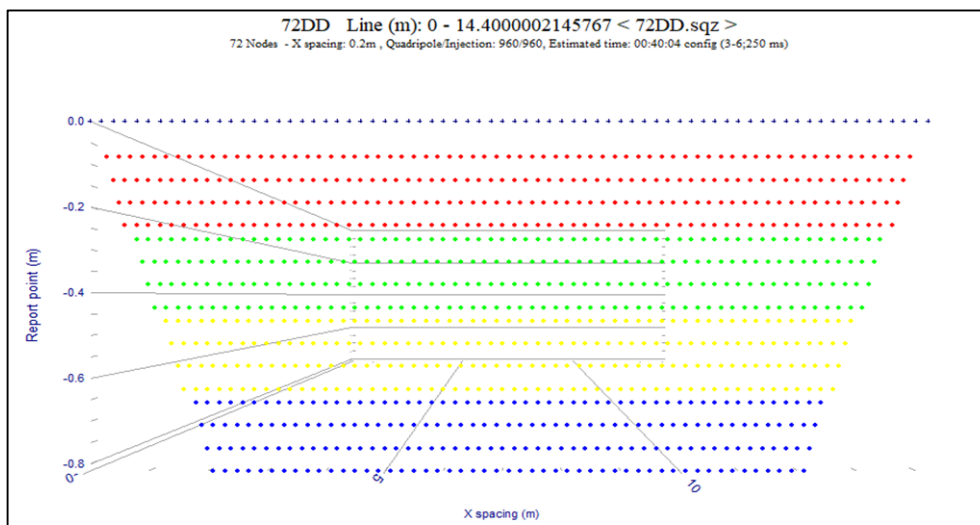


Figure 2-3 Sequence creation for the ERT in Electre Pro Software: (a) Linear grid setting (b) Depth grid setting (c) visualisation of expected output

2.2.3 Tests in the recently refurbished HSFCW

ERT was also applied on a recently refurbished HSFCW for comparison with the ERT results from the initially tested clogged HSFCW. The refurbished system

had surface area of 400 m² (20 × 20 m), planted with *Phragmites australis* and was filled with gravel (grain diameter of 8–12 mm) to a depth of about 0.60 m (Figure 2-4). The outlet pipe was positioned at 50 cm from the bottom, following the design guidance to maintain a water level of 50 cm in the HSFCW. Dipole-Dipole and Wenner arrays were used to measure electric resistance of the substrate along a line perpendicular to the direction of flow corresponding to line D-D across the mature HSFCW (Figure 2-2 a).



Figure 2-4 Recently refurbished HSFCW

2.3 RESULTS

2.3.1 Visual Inspection of the Mature HSFCW

Visual inspection of the HSFCW was conducted and overall, 5 different surface conditions were identified across the surface namely: dry reed bed surface without plants, reed bed surface with water ponding, dry reed bed surface with plants, reed bed surface with plants and water ponding and reed bed surface with surface flow (Figure 2-5 a). The overall surface of the HSFCW was covered in sludge mainly comprising of plant debris and leaves. The work was carried out in winter, which meant low density of plants across the CW with only 25% – 30 % of the CW area populated with reeds. Sludge depth varied between 0 to 24 cm across the surface (Figure 2-5 b), with the first 6 meters from the inlet presenting a higher accumulation with a minimum of 7cm and maximum of 24 cm. The remaining half had relatively lower sludge depths ranging from 0 to 11 cm. Comparing the sludge accumulation near the inlet in direction perpendicular to

the flow, it was observed that higher sludge was accumulated on the left half of the CW at points 1 and 4, with 24 cm and 21 cm, respectively. Right half of the CW had lower sludge depth of 12 cm at point 7. This spatial variation of sludge depths indicates an uneven distribution of wastewater loading across the CW, which can be an indication of clogging and development of preferential flow paths. Furthermore, water flow on surface of an HSFCWs indicates that subsurface is blocked and the CW is not able to operate according to its intended design due to clogging (Tang et al., 2017).

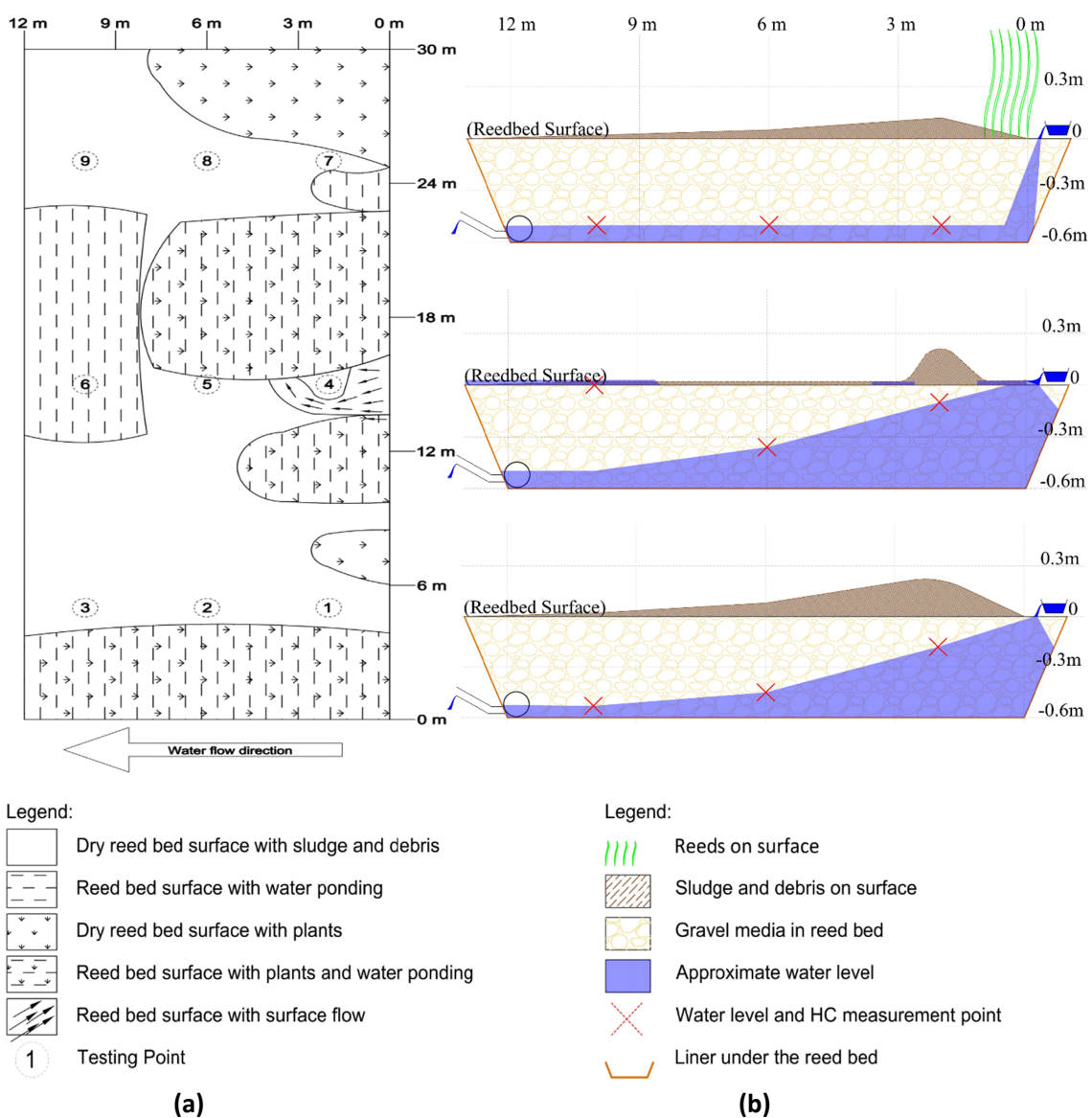


Figure 2-5 (a) Plan view of HSFCW surface condition (b) Profile view of sludge and water depth across the HSFCW

Significant water ponding on the surface around point 6 and surface flow near point 4 were observed, indicating subsurface clogging, short-circuiting and unequal distribution of wastewater in the subsurface. The unequal distribution of water across the wetland media was confirmed by the varying water levels observed on the subsurface while digging holes at different locations across the CW (Figure 2-5 b). Higher water levels near the inlet point and lower water levels near the outlet are expected in HSFCWs as it reflects higher solid loading near the inlet which keeps decreasing as the wastewater flows through the media towards the outlet (Ergaieg et al., 2021). However, the uneven water levels in the direction perpendicular to the flow is an actual indication of unequal water distribution. Water levels of 38, 46 and 10 cm were recorded at points 1, 4, and 7, respectively, which located at an equal distance of 2m from the inlet. At a distance of 6 m from the inlet, water levels were 24, 33 and 10 cm at points 2, 5, 8 respectively, whereas at 10 m from the inlet at point 3 and 9 water levels were 7 and 10 cm respectively. There was 3 cm of water over point 6 (water ponding), which was assumed to be fed from the surface flow near point 4 and not connected to the subsurface water levels. This assumption was made because this location was above the outlet point and if the subsurface media was not severely clogged, water level would have naturally gone down to the outlet level under gravity.

2.3.2 Hydraulic Conductivity and Tracer Testing

Hydraulic conductivity values across points 1, 2, 3 and points 7, 8, 9 ranged from 0.9×10^{-3} to 4.8×10^{-3} m/s (Figure 2-6 a & c). Similar values were observed at corresponding inlet, mid and outlet points with increase in hydraulic conductivity values from inlet to midpoint and subsequently near the outlet. This could be explained by the higher pollutants load present in the areas near the inlet points, which results in higher solids accumulation and a reduction in permeability of the media near the inlet compared to the midpoints and outlet (Pedescoll et al., 2009). Hydraulic conductivity values along points 4, 5, 6 showed an abnormal trend with values of 2.0×10^{-3} , 2.4×10^{-3} and 0.1×10^{-3} m/s respectively (Figure 2-6 b).

These observations are consistent with results of the visual inspection. The lower hydraulic conductivity recorded in point 6 confirmed the lower permeability of media resulting in water ponding as water could not infiltrate through highly clogged media. Furthermore, the lower hydraulic conductivity at point 4, relative to point 1 and 7, along with the presence of surface flow near the area, evidenced severe clogged at this point. Hydraulic conductivity values provide information regarding the distribution of permeability in media at different locations in the HSFCW. However, these staggered point values cannot provide visualisation of the subsurface conditions, as hydraulic conductivity provides average value across the depth at one location while subsurface conditions vary across length as well as depth of HSFCW profile. Multiple data points of hydraulic conductivity across depth and length would be required to achieve reliable information of the subsurface conditions. Undertaking these tests on multiples locations across the CW may not be feasible on a regular basis due to their invasive nature. Hence, there is requirement of non-invasive testing procedures like ERT, which can provide 2D profile of the subsurface.

Tracer test results indicate the variation in concentration of tracer with time in the effluent (Figure 2-6 d). Before injection of the tracer, the sensor was showing value of 7 ppb at the outlet that can be due to suspended particles in the effluent. 7ppb is assumed to be baseline for this tracer test. Rhodamine was injected in the system at a 1ppm concentration from inlet at start time taken as 00:00 and the sensor at the outlet started measuring the rhodamine concentration after 11 minutes. The peak concentration at the outlet was recorded after 16 minutes followed by two smaller peaks at 27 and 54 minutes. The concentration dropped to the base value after 2 hours. Different peaks may indicate presence of different preferential flow paths in the CW. Moreover, drainage of most part of the rhodamine within 16 minutes indicate that most of the water is going through short circuiting in the system and is not getting enough interaction with the subsurface environment to get treated. This low hydraulic retention time, reflected by the early peak in the RTD (retention distribution time) curve (Figure 2-6d), can be explained by the lower positioning of the outlet pipe, resulting in a higher hydraulic gradient. This allows water to flow through unclogged areas of the subsurface

and develops preferential flow paths. Typical retention time for wetlands range from 7 hrs to 9 days based on area, pollutant loads as well as spacing in the media (Ghosh & Gopal, 2010; Toet et al., 2005).

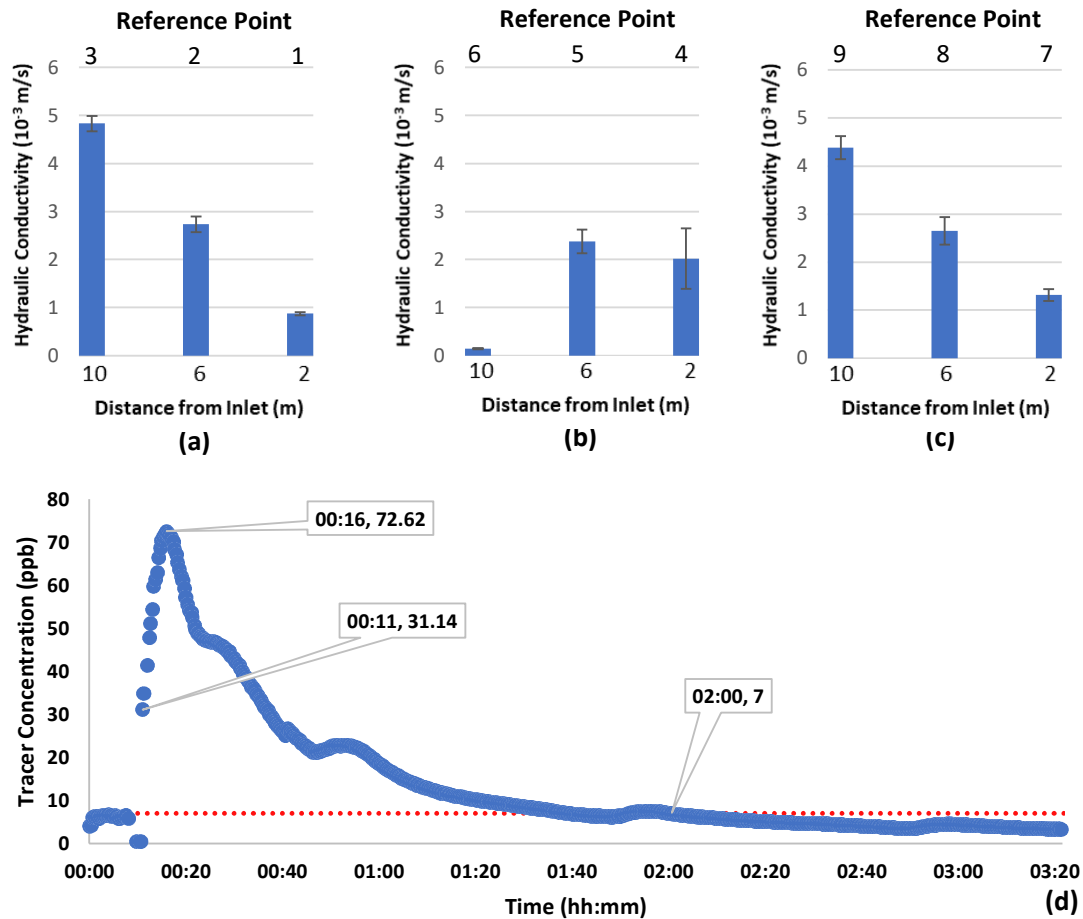


Figure 2-6 Hydraulic conductivity results across (a) section A-A (Reference points 1,2,3), (b) section B-B (Reference points 4,5,6), (c) section C-C (Reference points 7,8,9) and (d) tracer test results. Red line in tracer test results is indicating the base values measured by sensor at outlet point without the tracer.

2.3.3 Electric Resistivity Tomography of Mature HSFCW

Electric resistivity values measured for the three lines along the flow direction using Dipole-Dipole array and Wenner Array, show significant variation (Figure 2-7). Variation in ERT results shows that it has effectively detected the changes in subsurface conditions of the HSFCW corresponding to resistivity ranges between 10 to 4378.9 ohm.m. The overlay of visual inspection (Figure 2-5 b) and

ERT results of the Dipole-Dipole array (Figure 2-7 a, c & e) shows that this technique was effective in detecting the water levels in the HSFCWs.

The ERT outcomes, analysed through the dipole-dipole array comprising 9 points coinciding with water level measurements obtained through visual inspection, consistently exhibited the same range of sky-blue colour referring to resistivity values ranging from 50 to 170 ohm.m (Figure 2-7 a, c & e). Notably, these resistivity values were considerably lower than those recorded (up to 4378.9 ohm.m) in the clogged area of the wetland. Furthermore, the dipole-dipole array was effective in outlining the liner boundary for section A-A and section C-C represented by yellow and red shaded areas for corresponding values of more than 384 ohm.m (Figure 2-7 a & e). Uneven variation in the liner boundary detected for section B-B was attributed to significant fluctuations along the line in the form of water ponding, surface water flow and high levels of clogging that might have influenced interpolation results (Figure 2-7 c). These findings align with the investigations of Liu et al. (2022), which quantified accumulated clogging matter in various segments of full-scale wetland systems and demonstrated a negative correlation between ERT resistivities and clogging matter fractions (v/v), with a linear slope of 0.900 and an R^2 value of 0.902.

The results obtained from the Wenner array also facilitated the determinations of approximate liner boundary depths, with contour range of value higher than 384.4 ohm.m which was consistent with observations made using the Dipole-Dipole array. However, the resistivity values from the Wenner array did not show much consistency with the observed subsurface water levels (Figure 2-7 b, d & f). It is noteworthy that a previous study also highlighted the limited accuracy of the Wenner array in HSFCWs when compared to other array method (Liu et al., 2022). This discrepancy may be attributed to Wenner array being relatively sensitive to vertical changes in the subsurface resistivity but less sensitive to horizontal changes in the subsurface resistivity (Uwaezuoke et al., 2021). Overall, it can be concluded that the Dipole-Dipole array was effective in detecting unequal distribution of water in the wetlands media and can help visualise clogging levels in HSFCWs.

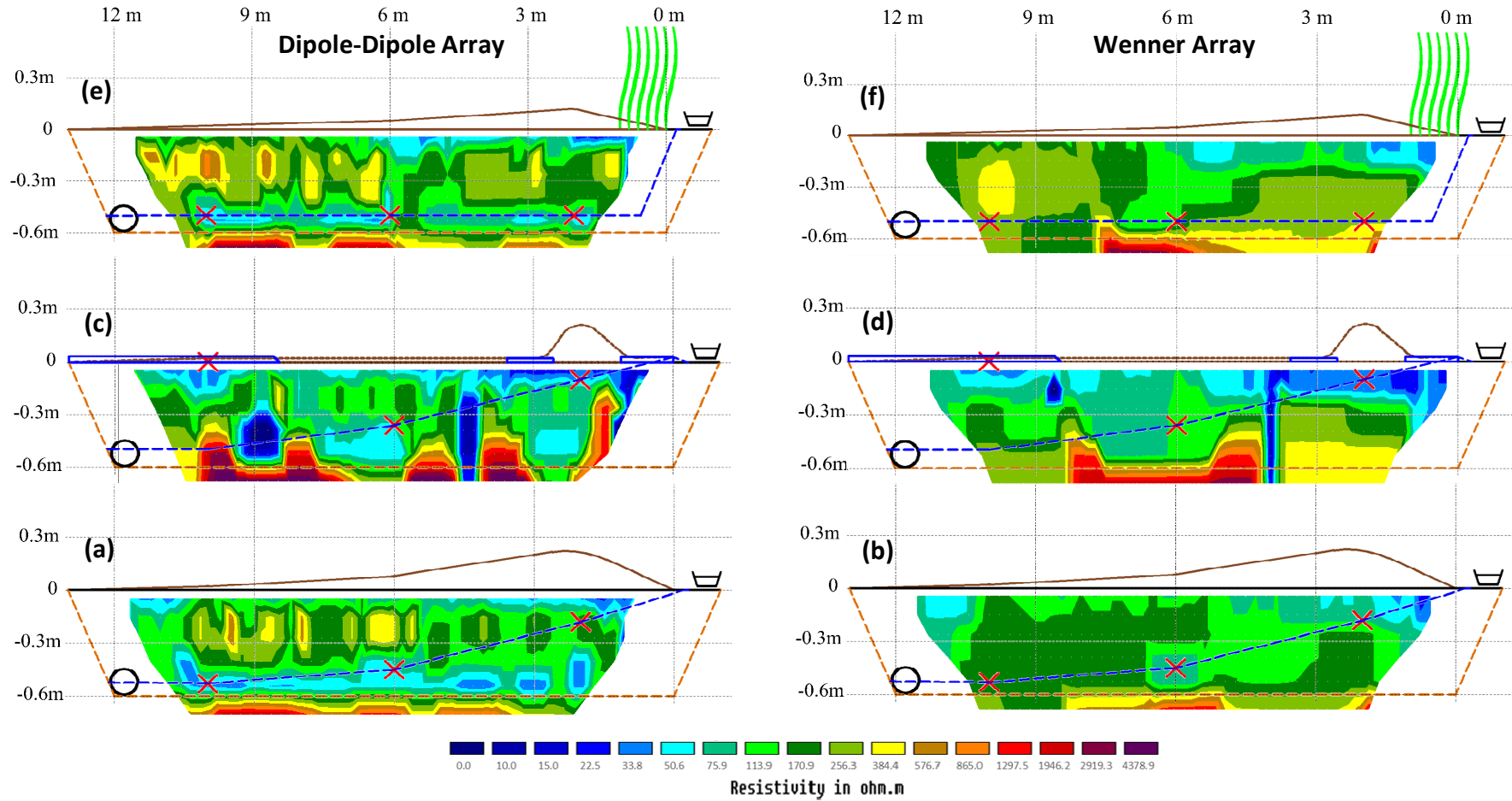


Figure 2-7 Overlapping of visual inspection results from (Figure 2-5 b) over ERT results for Dipole-Dipole array and Wenner Array (a) and (b) section A-A, (c) and (d) section B-B and (e) and (f) section C-C. Blue dashed line is showing approximate water levels, brown dotted line is showing approximate liner location and red crosses are showing water level measurement points.

It was concluded that ERT through Dipole-Dipole array was effective in identifying the subsurface liner location as well as the location of water in the media at different depths. Wenner array results did not have as much resolution as that of Dipole-Dipole array however, it has been able to demark the liner location as well as water distribution along the HSFCW surface.

2.3.4 Electric Resistivity Tomography of Recently Refurbished HSFCW

Comparison of ERT results for a mature CW not refurbished over 10 years and the recently refurbished CW show significant differences (Figure 2-8), further exposing the feasibility of the ERT methodology to detect clogging matter and asset CWs refurbishment needs. Variation of resistivity values from 15 to 1297.5 ohm.m in the subsurface of the heavily clogged CW is visible in Dipole-Dipole and Wenner Array results (Figure 2-8a and b). Both the Dipole-Dipole and Wenner array results show lower variations of electric resistivity 22.5 to 75.9 ohm.m in the media of the recently refurbished wetland (Figure 2-8 b and c). These lower values and slight variation in contour indicate that ERT have been able to visualise uniform subsurface conditions across the newly refurbished CW. Significant variations in contours for clogged CW indicate that ERT is sensitive to clog accumulation in subsurface of CWs. Results for both CWs were not able to identify liner boundary with much accuracy indicating lower spatial resolution compared to Figure 2-7 which can be improved by reducing electrode spacing.

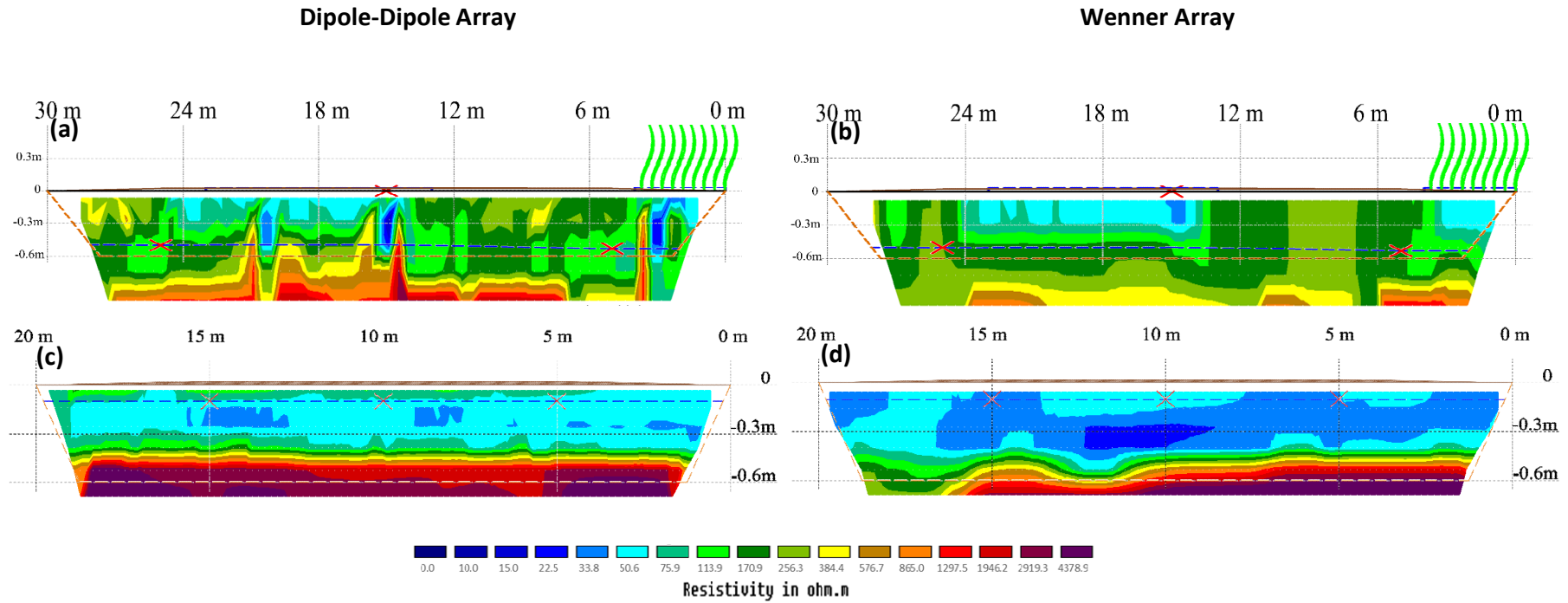


Figure 2-8 Overlapping of visual inspection results from (Figure 2-5 b) of ERT results along section D-D for (a) Dipole-Dipole array on unrefurbished CW, (b) Wenner Array on unrefurbished CW, (c) Dipole-Dipole array on recently refurbished CW and (d) Wenner Array on recently refurbished CW. Blue dashed line is showing approximate water levels, brown dotted line is showing approximate liner location and red crosses are showing water level measurement points.

2.4 DISCUSSION

2.4.1 ERT and Visualisation of Subsurface Conditions of HSFCW

The subsurface clogging levels of a mature HSFCWs was measured by ERT, while the CW remained operational, and compared with conventional clogging assessment methods of visual inspection, hydraulic conductivity, and tracer testing. Consistent results were obtained from all the methods indicating subsurface clogging in the system. However, visual inspection and hydraulic conductivity provided only point data, requiring further assumptions to estimate subsurface conditions (Figure 2-5 & Figure 2-6 a, b &c). The tracer test, which measures the overall hydrodynamic condition of the HSFCW, indicated a noticeably short retention time (Figure 2-6 d). However, these conventional tests were unable to provide reliable visualisation of the subsurface condition of the HSFCW and could not inform the feasibility of conducting a targeted and cost-effective partial refurbishment to recover the system. In contrast, the ERT results provided visualisation of the subsurface media condition, with indications of unequal distribution of water and media with varying electric resistivity (Figure 2-7 & Figure 2-8). Furthermore, lower resistivity values detected near areas of identified water accumulation were consistent with observations of other researchers (Ergaieg et al., 2021; Fang et al., 2022; Liu et al., 2022). These 2D illustrations can identify locations with higher or lower clogging and support understanding of the probable phenomenon causing the clogging in HSFCWs.

ERT has proven to be a sensitive method for monitoring water levels in the field (Brunet et al., 2010; de Jong et al., 2020); thus, the ERT results in this study (Figure 2-7 and 2-8) aligned with visually inspected water levels in the two CWs. These 2D illustrations also enable the identification of locations exhibiting varying degrees of clogging, providing valuable support for proactive clogging remediation strategies. While lowering the outlet pipe for controlling water flow path is a passive measure to sustain HSFCWs, it does not address clogging issues or impede clogging development. The integration of ERT measurements enhances our ability to extend the lifetime and optimise the efficiency of HSFCWs in wastewater treatment.

2.4.2 Differences between ERT arrays

Comparing the results of different arrays of ERT with the hydraulic conductivity and physical inspection results, it was observed that Wenner array is more sensitive to the presence of water in the system, while Dipole-Dipole Array provides a better resolution of media density (Figure 2-6 & Figure 2-7). The variations in the results were comparable with the physical observations made on the site as well as the hydraulic conductivity values. Both methods should be applied in combination to obtain a better estimation of internal clogging condition of a HSFCW.

The Wenner array was not able to identify subsurface boundaries with high accuracy, consistently with other studies (Liu et al., 2022). The Dipole-Dipole array provided relatively accurate boundaries especially liner at 0.6 m depth. Both configurations identified local differences in the hydraulic conductivity of the system, indicating a non-uniform distribution of water and organic clog matter, along with dry or clear gravel media, which is consistent with findings from other researchers (Liu et al., 2022; Marzo et al., 2018). This study provides information regarding effectiveness of Dipole-Dipole and Wenner arrays to visualise subsurface conditions of operational full scale HSFCWs, which have not been explored earlier. This information can be used along with previous studies on lab scale models and other ERT arrays to develop a better methodology to use ERT for monitoring of clogging development in HSFCWs.

The ERT results along section D-D for the unrefurbished and recently refurbished HSFCWs had lower resolution compared to section A-A, B-B and C-C. However, these results showed significantly higher resistivity variations in the unrefurbished system and uniform resistivity for refurbished HSFCWs indicate that ERT is sensitive to subsurface clogging even with wider spacing between the electrodes. However, ERT with electrode spacing of 0.2m or lower will be more effective for regular monitoring of subsurface conditions of HSFCWs in operation. Although, data processing and interpretation is a complicated process at the moment, however further studies and more data can help standardise the process. Once optimised ERT methodology has been developed it would not require high level

skills for regular monitoring of the HSFCWs. ERT did not involve any destructive activity to the CW bed, moreover, data collection and interpretation can be undertaken within a couple of days. This can provide a cost-effective option to HSFCW operators to regularly monitor clogging development and take proactive clogging remedial measures, which will be cost effective and sustainable approach.

2.4.3 Further Implementation Potential

The findings from this study demonstrated that ERT is an effective method for identifying areas of clogging in HSFCWs, providing a non-intrusive alternative to estimate subsurface clogging levels and pinpoint the locations in need of intervention. As a result, operators can plan more targeted refurbishment strategies, reducing downtime and increasing treatment efficiency while minimising the risk of unanticipated malfunctions like short-circuiting of HSFCWs.

The ERT methodology also has potential for further improvements by exploring electrode spacing of less than 20cm. Use of ERT for regular monitoring of CWs can also provide useful information on the impact of hydraulic loading rate and vegetation on the subsurface clogging process. Moreover, ERT can also be combined with other geophysical methods like Ground Penetrating Radar (GPR) to provide a more comprehensive understanding of subsurface conditions in HSFCWs (Matos et al., 2019). Use of multiple techniques can enhance visualisation of subsurface condition and resolve limitations of individual methodologies.

Recent studies have also explored the use of advanced ERT techniques such as time-lapse imaging and inverse modelling for more accurate subsurface characterisation in CWs (Marzo et al., 2018). These techniques provide enhanced imaging capabilities for monitoring clogging development and water flow in HSFCWs. Furthermore, research has also shown the potential of combining ERT with other non-intrusive techniques such as Ground Penetrating Radar and Magnetic Resonance Imaging for improved subsurface characterisation (de Matos et al., 2018; Ergaieg et al., 2021).

By incorporating these developments, ERT has the potential to become a valuable tool for frequent monitoring and management of subsurface conditions in HSFCWs, facilitating more efficient and cost-effective CW operation.

2.5 CONCLUSION

This study has demonstrated the effectiveness of ERT in assessing clogging levels in CWs by providing subsurface profiles of the clogging condition and water levels in HSFCWs. It is important to note that while the Wenner array provides better depth resolution and can detect variations across depth more effectively, it has lower depth coverage near the edges of the system. In contrast, the Dipole-Dipole array is more sensitive to changes in the horizontal direction and has better depth coverage near the end of the line. Both arrays complement each other in understanding clogging development in the subsurface of a wetland. Therefore, it is recommended that results from the Dipole-Dipole and Wenner arrays are analysed in parallel to obtain a better understanding of the subsurface profile.

Moreover, the ERT method can provide a non-intrusive alternative approach for estimating subsurface clogging levels in HSFCWs and identifying specific locations that require intervention. This can help operators plan more focused refurbishment strategies, resulting in cost-effective operations, reduced downtime, increased treatment efficiency of the CWs, and a decreased risk of unanticipated malfunctions like short-circuiting of the HSFCWs.

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