FLOATING VEGETATED ISLAND RETROFIT TO TREAT STORMWATER RUNOFF

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ABSTRACT

A novel approach to improve retention basin water quality performance is retrofit with a floating vegetated island (FVI) to introduce wetland-like vegetation. Limited studies have identified the capability of pollutant removal of FVI but none have dealt with treatment efficiency at a full scale specifically for stormwater.

This paper presents the expected different pollutant removal pathways induced by a FVI as well as the monitoring methodology used to assess the overall efficiency of a retention pond with a FVI compared to an unvegetated one. Sampling and analysis methodologies to quantify the magnitude of each pollutant removal pathway are explained and a preliminary analysis of plant roots from a well established FVI is presented. The results show that the roots hanging in the water below the FVI can host microorganisms. Furthermore they become covered by deposits (clay and iron plaques) which have sorption capacity for elements like sulphur and zinc. Preliminary analysis confirms that roots surfaces below the FVI can act as a sink for pollutants.

KEYWORDS

stormwater, treatment, floating vegetated island, retention pond, metals, nutrients

1 INTRODUCTION

A floating vegetated island (FVI) is a vegetated device typically installed on the surface of a pond in order to improve water quality treatment. It is composed of a floating plastic mat and vegetation planted within it, allowing the roots to hang into the water (Figure 1).

Figure 1: Left: FVI on the West Pond (Rosedale) in Auckland, NZ after 1.5 years establishment, right: cut section of a FVI

FVIs are increasingly used for wastewater treatment in New Zealand. These systems have demonstrated very good nutrient removal efficiency as well as TSS removal for domestic wastewater (Stewart, 2007, Zhang et al., 2010). Nevertheless, they are still little used for stormwater treatment. Three trial sites (ponds retrofit with FVIs) have been set up in New Zealand for stormwater treatment up to now: one in Rosedale, North Shore (figure 1), one in Bayside reserve, Rothesay Bay and one in Silverdale (current research project).

The present study has two main objectives. The first one is to quantify the water quality (copper, zinc, nitrogen, phosphorus, solids) treatment from a retention basin retrofit with a FVI against a retention pond without island. This will be addressed in a field trial of a side by side evaluation. The second is to assess the relative magnitude of the different pollutant removal processes. An attempt will be made to link the physical condition induced by the island (pH, Eh, DO) to the occurrence of each removal pathway. The size and design of the FVI should influence these parameters and thus should have a direct effect on the system efficiency. This paper provides a background on the expected pollutant removal pathways induced by an FVI, and the methodology used to assess these pathways as well as the global performance of a FVI in a side by side field study. A preliminary analysis of the roots developing below a FVI is also presented.

2 PROJECT PRESENTATION AND PRELIMINARY ANALYSIS

2.1 BACKGROUND

2.1.1 WATER QUALITY TREATMENT BY HYDROPONIC SYSTEMS

Previous studies have identified the capability of pollutant removal of a FVI or a system composed of floating plants (Gao, 2008, Hubbard, 2010, Li et al., 2010, Stewart et al., 2008, Tanner and Headley, 2011). These studies mainly reported the nutrient removal efficiency of these systems, which could be as high as 96 % NH_4 removal over 6.7 days and 85 % dissolved reactive phosphorus removal over 13.6 days (Headley and Tanner, 2007). Only one study (Tanner and Headley, 2011) dealt with metals treatment (copper and zinc) which are parameters of concern for stormwater runoff in Auckland and New Zealand. Nevertheless it was performed with mesocosm experiments (not in a full scale study). There is thus a lack of data on the metals remediation efficiency of a FVI at a field scale.

2.1.2 EXPECTED POLLUTANT REMOVAL PATHWAYS

It is assumed that metals and nutrients (nitrogen and phosphorus) can be removed from runoff by a hydroponic system (i.e. FVI) either by 1) uptake of pollutant by the roots, 2) sorption/precipitation on root surface (for metals and phosphorus), 3) precipitation/sorption/binding to other particles (for metals and phosphorus) below the island, and subsequent settlement on the bottom of the pond 4) nitrification/denitrification processes (for nitrogen) in the rhizosphere and just below the floating mat, or 5) entrapment of pollutants associated to particles in the roots net, and subsequent settlement on the bottom of the pond.

Pathway 1. Radial Oxygen Loss (ROL) through the roots can cause plants to increase the redox potential (Eh) in the rhizosphere (Jespersen et al., 1998, Wießner et al., 2002). Furthermore pH can be modified in the surrounding of the roots due to cation/anion exchange (Nye, 1981, Riley and Barber, 1971), bacterial activity in the rhizosphere (which produces organic acids that can lower the pH (Hietala and Roane, 2009)) and the release of rhizodeposits which can drop the pH (Nye, 1981). While degrading organic substances, bacteria and fungi present on the roots, produce citric acid and oxalic acid which can form soluble metals complexes (Strasser et al., 1994a, Strasser et al., 1994b). All these processes, impacting the solubility and thus the bioavailability of pollutant to the plants, enable the pathway 1.

Pathway 2. Due to ROL and the presence of oxidizing bacteria, some iron or manganese plaques (metal hydroxides) can be formed on the surface of roots (Emerson et al., 1999, Batty et al., 2002). Metals, like Cu and Zn, or phosphorus can be sorbed on these plaques (Ye et al., 2001, Ye et al., 1998, Batty et al., 2002).

Pathway 3. It is thought that under anaerobic conditions, which could appear below the FVI due to a lack of water aeration particularly between storm events, sulphate can be reduced as sulphide which can precipitate as insoluble metal sulphide (Van Der Welle et al., 2006). Of course the dominance of the different metal sulphides complexes depends on the concentration of available sulphide, Eh and pH (Zhang, 1994). Regarding phosphate ions, they can precipitate with metallic cations (as Fe, Al) or Ca (Vymazal, 2008). Likewise, under aerobic conditions, insoluble phosphates are precipitated with ferric iron Fe(III), calcium and aluminium (Scholz and Lee, 2005). Phosphate is known to have sorption affinities with soil or sediment particles that contains Al, Fe or Mg (Vymazal, 2008) and can thus accumulate on their surface. Metals also have binding properties with organic compounds (Nierop et al., 2002), which should be present below the island because of root die back and exudates. Metals bound to organic matter can flocculate with other particulate matter and settle on the bottom of the basin.

Pathway 4. The aerobic condition near the roots and the presence of nitrifying bacteria could induce nitrification and thus removal of ammonium and nitrite (Gersberg et al., 1986). Regarding nitrate, it has been reported that an artificial floating island could serve as a support for denitrifying bacteria and thus induce denitrification (Stewart et al., 2008).

Pathway 5. It has been demonstrated that an FVI can reduce the turbidity of water by entrapping particulates in the root net (Headley and Tanner, 2007). After entrapment in the root biofilm, particulates may subsequently settle on the bottom of the pond.

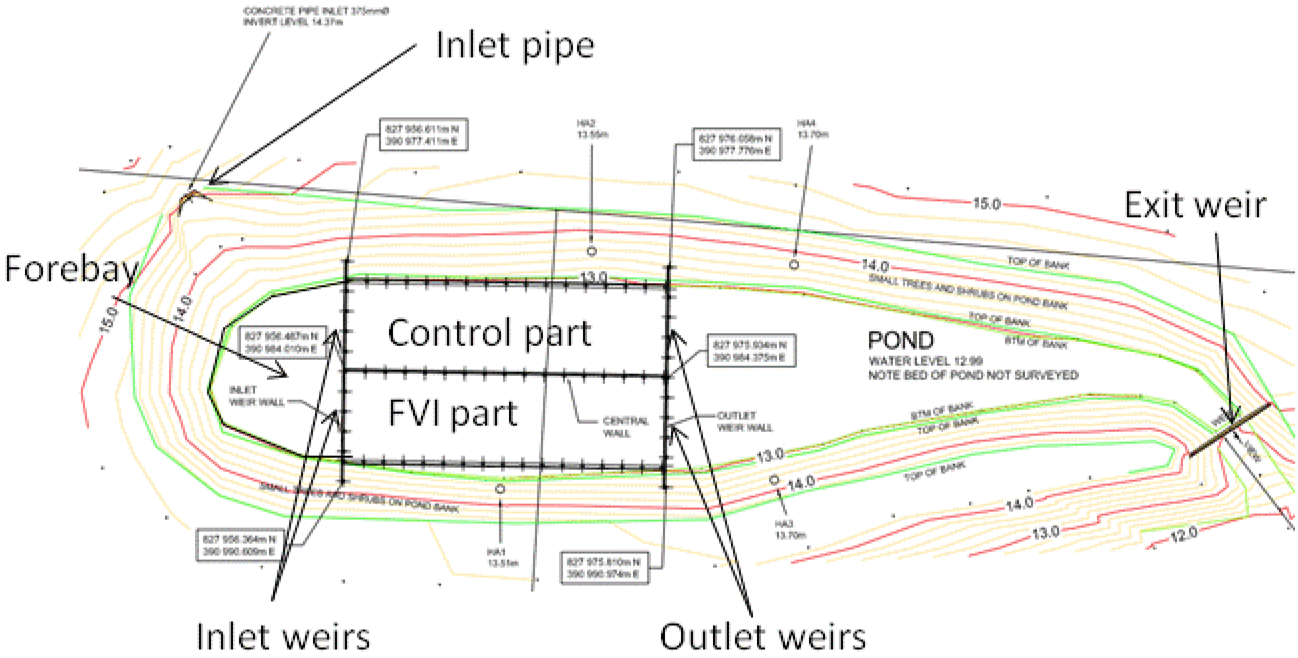
The proportion of each pathway induced by a FVI to remove pollutants from water is unknown. Nonetheless it could have a significant impact on the maintenance aspect of an FVI. If the major pollutant removal process is the immobilization of pollutants in the sediment, this would have an impact on operational maintenance. If the accumulation of the pollutant in plant tissues is the major pathway, plants might be saturated with pollutants after a certain period. The assessment of each pathway will provide a basis for maintenance operation. Furthermore, this will help to improve design for better treatment. Each pathway is influenced either by the physicochemical condition of the water induced by the island (pH, Eh, DO) or by the presence of the plants themselves. The size and design of the FVI (plants/m^2) should influence these parameters and thus should have a direct effect on the occurrence and magnitude of each pathway.

2.2 EXPERIMENTAL SITE

The experimental site is located about 40 km north of Auckland, New Zealand, along a highway interchange (crossing of State Highway (SH) 1 and SH17) in Silverdale (figure 2). This pond was constructed as part of the highway realignment from Silverdale to Okura River in 1999. It primarily serves a water quality function (rather than peak flow control). The catchment is approximately 1.7 ha, and 75 % impervious, comprising the south bound on-ramp and a section of the full carriageway width of SH1, including shoulder and grass berms. The pond has been bifurcated into parallel sections (100 m^2 each), with a permanent water depth of 0.75 m, in order to allow a side by side study (figure 3). A 50 m^2 FVI planted with *Carex Virgata* (~16 plants/m^2) was installed in the beginning of December 2010 in one partition while the other partition serves as a control. The forebay (about 100 m^2) is common to both sections and has a permanent pool of 1.09 m depth. The pond is expected to receive 330 m^3 stormwater runoff during a 24h storm event of 28.3 mm rainfall (water quality volume).

Figure 2: Experimental site location (Google-Maps)

Figure 3: Partition sections built in the pond



2.3 MATERIAL AND METHODS

2.3.1 SITE INSTRUMENTATION

Instrumentation at the site is described in figure 4. Three pressure transducers (INW AquiStar® PT12, 3 m range) for continuous measurement of water level have been installed upstream of weirs to calculate the inflow and outflow of each partition section using a weir equation. Three ISCO 3700 automated samplers (one at the upstream of the inlet weirs and two just upstream each outlet weir) have been installed to collect storm event samples. One continuous monitoring dissolved oxygen (DO) probe (D-Opto logger, Zebra-Tech Ltd) has been installed in the middle of the island just beneath the FVI.

Eleven removable planted pots are incorporated into the island to allow easy access to sample roots (figure 5). Ten tubing ports have been installed in five different locations to allow water sampling at two different depths below the island (just below the island (10 cm depth) and at 40 cm depth).

Figure 4: Pond instrumentation map (not to scale)

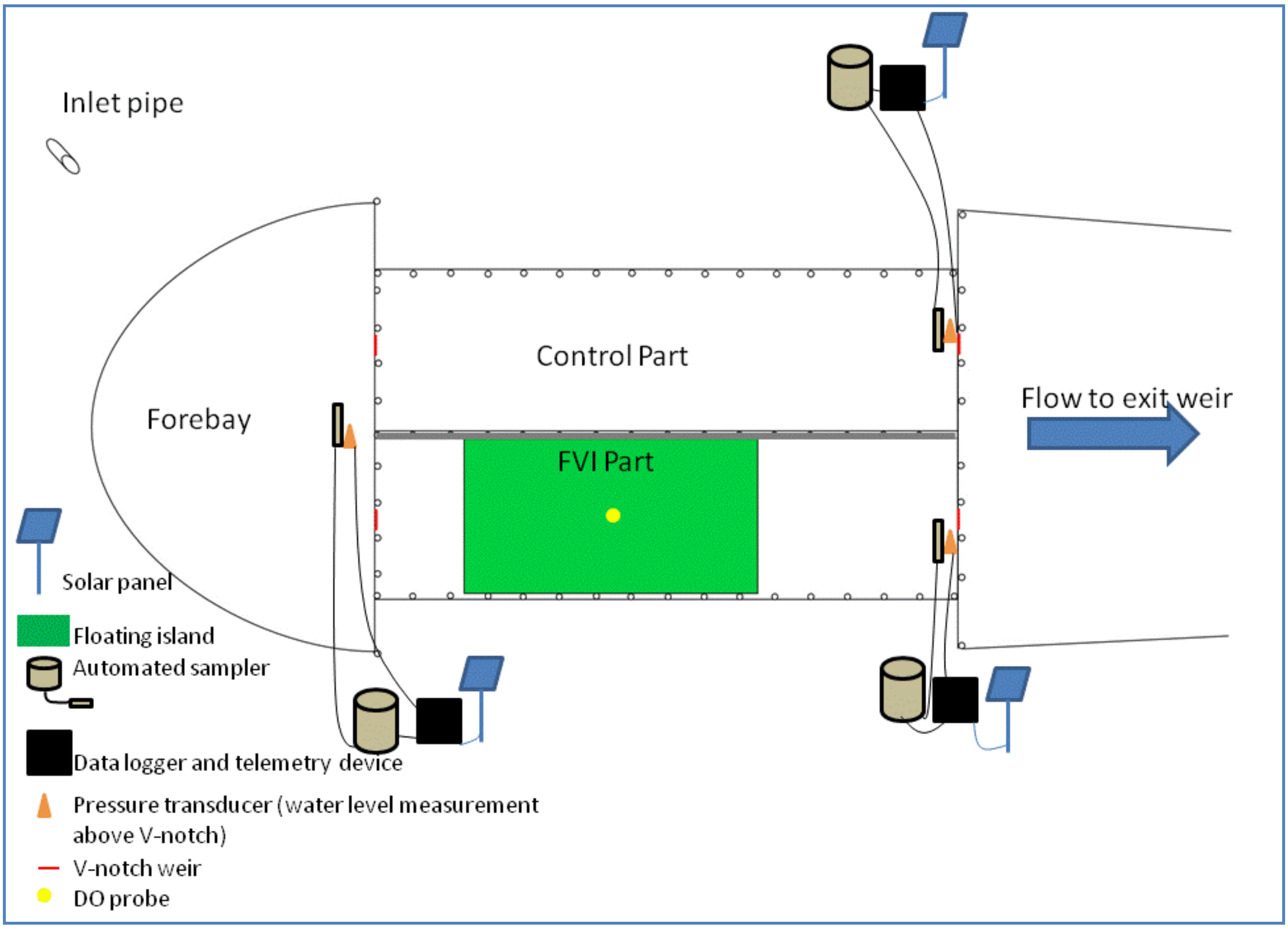


Figure 5: FVI with yellow removable pots and tubing for water sampling below the island (December 2010)

2.3.2 SAMPLING AND *IN-SITU* MEASUREMENTS

INFLOW/OUTFLOW DURING STORM EVENT

Automated samplers are used to collect discrete samples at specified points over the hydrograph. The inlet pollutant concentration should be the same for both partitions, so only one point is sampled for inlet concentration, just upstream of the inlet weirs (the downstream end of the forebay). Pollutant concentrations at the outlet of each partition are monitored independently. Individual (discrete) samples are collected over the duration of the storm hydrograph at prescribed time intervals. Flow-weighted composite samples are analysed to determine event mean concentrations (EMCs). The two first samples collected from each storm at both outlets are analysed separately while the rest of the samples are analysed as a composite sample (aliquots from the first two samples are also included in the composite). Indeed global pollutant removal efficiency might not be detectable using EMCs if the water which is collected comprises runoff of the current storm event (and thus not subject to extended treatment by the FVI). However, plug flow theory suggests that at least at the beginning of the storm, the water discharged should have received the most treatment. Total and dissolved copper and zinc (TCu, DCu, TZn, DZn), nitrite (NO_2^-), nitrate (NO_3^-), ammonium (NH_3+NH_4^+) , total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), total suspended solids (TSS), total dissolved solids (TDS) and volatile suspended solids (VSS) are analysed. The purpose of these analyses is to determine the event mean concentrations (EMCs) and the overall system pollutant removal efficiency.

INTER-EVENT WATER COLUMN MONITORING

In order to assess the impact of a FVI on aerobic/anaerobic conditions and nitrification/denitrification process that could happen just below the mat (expected to be anaerobic) and in the roots zone (expected to be aerobic), water analysis (NO_2^- , NO_3^- and NH_3+NH_4^+) and measurement of DO are performed in both partitions. Water column sampling and DO measurement are performed at 10 cm depth (corresponding to underneath the surface of the FVI) and at 40 cm depth, in the control partition and in the FVI partition. Sampling is performed using a peristaltic pump (Geopump 2, Misc Sampling Pumps) connected to the tubing permanently installed on the island (figure 5). DO measurement is done directly on site as samples are collected. Eh and pH in the water column are also measured during sampling at 40 cm depth to try to draw a relationship between the physical characteristics of each system (control part and FVI part) to their ability to immobilize and settle metals. Eh and pH have an impact on root plaque formation, as well as the soluble form or solid form of Cu and Zn, and thus on the amount of solid Zn and Cu that can precipitate and settle. The measurements are performed with a multiparameter probe (YSI 556 MPS).

SEDIMENT

In order to assess the impact of the FVI on immobilization of pollutants (as pollutants bound to metals hydroxides, to organic matter/humic compounds or precipitated as insoluble metals sulphides) and subsequent settlement or direct settlement of particulate pollutants, sediments samples are collected in the control part and FVI part. Sediment samples are analysed for total P, total Cu, total Zn. The analysis of the different forms of metals (exchangeable/carbonate form, fraction bound to hydroxides (Fe or Mn hydroxides), fraction bound to organic compounds and sulphides) is also performed. The redox potential in the sediment is measured in situ prior to the collection of the sediments at the location of the sampling points, using a combined Pt-ring electrode (Metrhom) linked to a portable Metrhom meter 826. Those data are interpreted in relationship with the different metals forms present in the sediment.

PLANTS

After 6 months of establishment, plant tissue samples will be collected to assess the pollutant concentration in shoots and roots. The purpose is to quantify the amount of pollutant actually taken up by the plant and to identify if uptake depends on location within the island. Biomass measurements will be made concurrently. The sampling and biomass measurement is performed thanks to the removable pot. Eleven sampling points will be analysed for P, N, Zn and Cu in shoots and roots. Cu and Zn on Fe/Mn plaques will be analyzed first to assess the absorption of these metals on roots surface.

SAMPLING SCHEDULE

The plants, sediments and water column sampling and associated Eh, pH and dissolved oxygen measurements are performed 4 times a year at each season. The first sampling mission was performed 5 days after the installation of the FVI. To avoid compromising the good establishment of plants, only an observation of the plants biomass development and general aspect of the plant are performed during the first 6 months. Nevertheless, 6 samples from the same batch planted on the island have been analyzed for P, N, Zn and Cu as a baseline. It is expected to collect and analyse between 15 and 20 storm events during the whole project (2 years).

2.3.3 ANALYTICAL METHODS

WATER

Cu and Zn concentrations in water samples are analysed by Flame AAS or Graphite AAS for low concentrations. The samples are filtered through a 0.45 µm cellulose ester filter prior AAS analysis for dissolved metal content. A microwave digestion is performed as per Standard Methods for the Examination of Water & Wastewater n°3030K (APHA, 2005) for total metals analysis prior AAS. TSS, TDS, VSS is performed as per Standard Methods for the Examination of Water & Wastewater n°2540 (APHA, 2005). Samples for NO_2^-, NO_3^-, (NH_3+NH_4^+), Total N, SRP, Total P analysis are sent to an external laboratory (Watercare) just after collection.

SEDIMENT

The sequential extraction of the different Cu and Zn forms is performed using the SM&T procedure as modified by Ianni (2001). Sediment for total Cu and Zn analysis are microwave digested (with HNO_3, HF) (Jumbe and Nandini, 2009). Extracts and digested samples are analysed by AAS. Sediments for TP analysis are sent to an external laboratory (Watercare).

PLANTS

Fe/Mn root plaques are extracted by DCB (dithionite–citrate–bicarbonate)-extraction (Lei et al., 2010, Taylor and Crowder, 1983). The extracted plaque is subsequently analyzed for Cu and Zn by AAS. Shoots and roots are then dried at 60°C until constant weight. Shoots and roots are sent to an external laboratory (Landcare Research) for analysis of Cu, Zn, N and P content.

Environmental Scanning Electron Microscopy (ESEM) and Scanning Electron Microscopy coupled with an Energy Dispersive Spectrometer (SEM-EDS) (Batty et al., 2002) will be performed periodically on some root samples over the project. These techniques allow a microscopic look at the root surface (resolution up to 10 µm) and to analyse (with the SEM-EDS) the composition of some selected areas on the root. It is being considered to highlight the iron/manganese plaques formed on the root surface and the different elements sorbed on those plaques. The ESEM allows looking at fresh samples (not dry) and microorganisms living on the surface of the root.

2.4 Preliminary analysis

Preliminary ESEM and SEM-EDS analysis of roots from a 2-yr old FVI confirms and expands the hypothesis for the pollutant removal pathway No1 (section 2.1.2). ESEM images of root samples collected from the West Pond FVI (Rosedale road, North Shore, figure 1) confirm that roots below a FVI can host microorganisms, as diatoms, commonly found in aquatic environment, are seen in figure 6 and 7. SEM-EDS of another root sample from the same FVI clearly show deposits on the surface of the root (figure 8). The EDS-1 analysis (figure 8c and 9) reveals that these deposits are composed mainly of silicon (Si), aluminium (Al) and iron (Fe). The particles accumulated are thus more probably clay and iron. The analysis of a localized part of this deposit (figure 8c and 10) highlights the presence of Zn and sulphur (S) which are incrusted in this deposit. Therefore, the images and analysis confirm that iron plaques can form on the surface of roots and sorb other pollutants, but clay can also play this role.

Figure 6: ESEM picture "WR1" of a fresh root sample

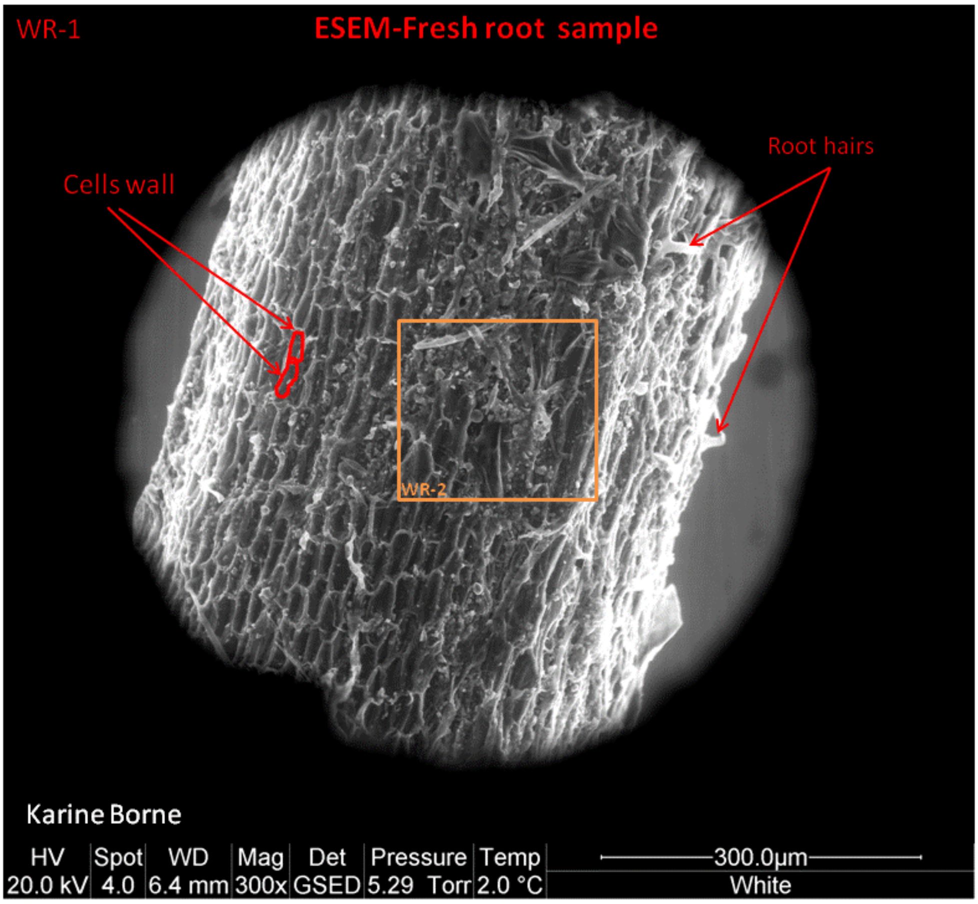


Figure 7: ESEM-"WR2" picture –Zoom-in of the "WR1" picture above

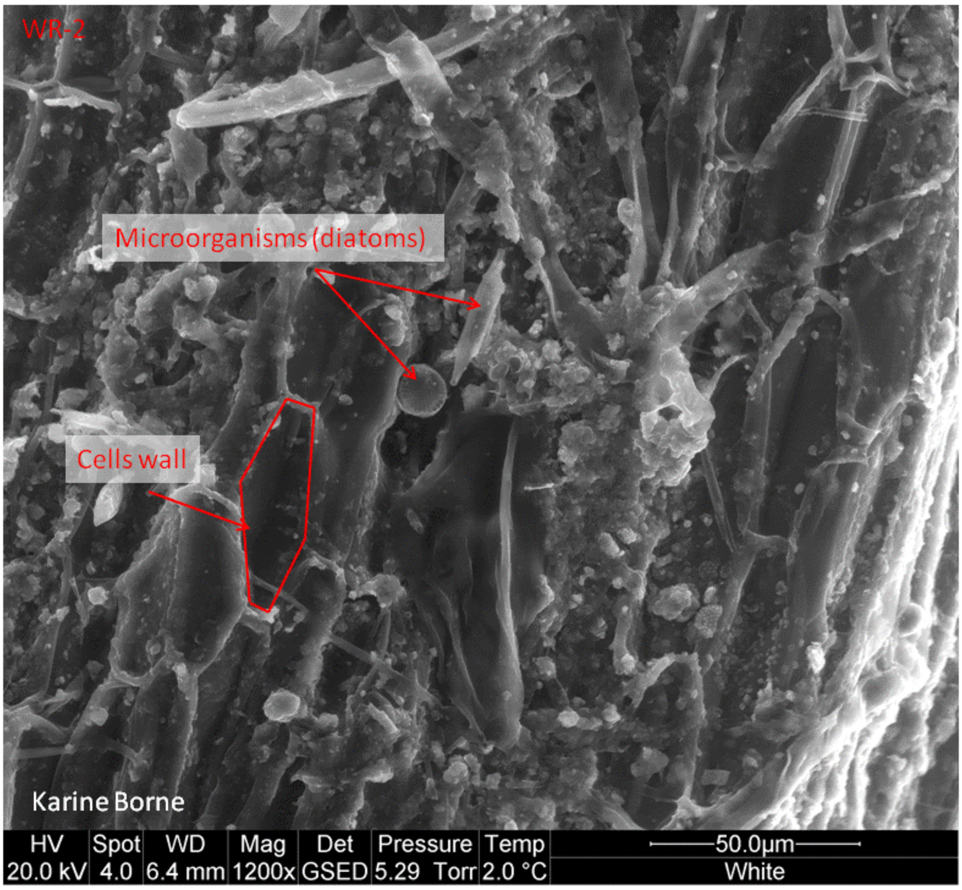


Figure 8: SEM-EDS analysis, a)Picture C1-1 of a root sample, b) Picture C1-2 zoom-in of the picture C1-1, c) Picture C1-3 zoom-in of the picture C1-2 showing the area selected for the EDS analyses

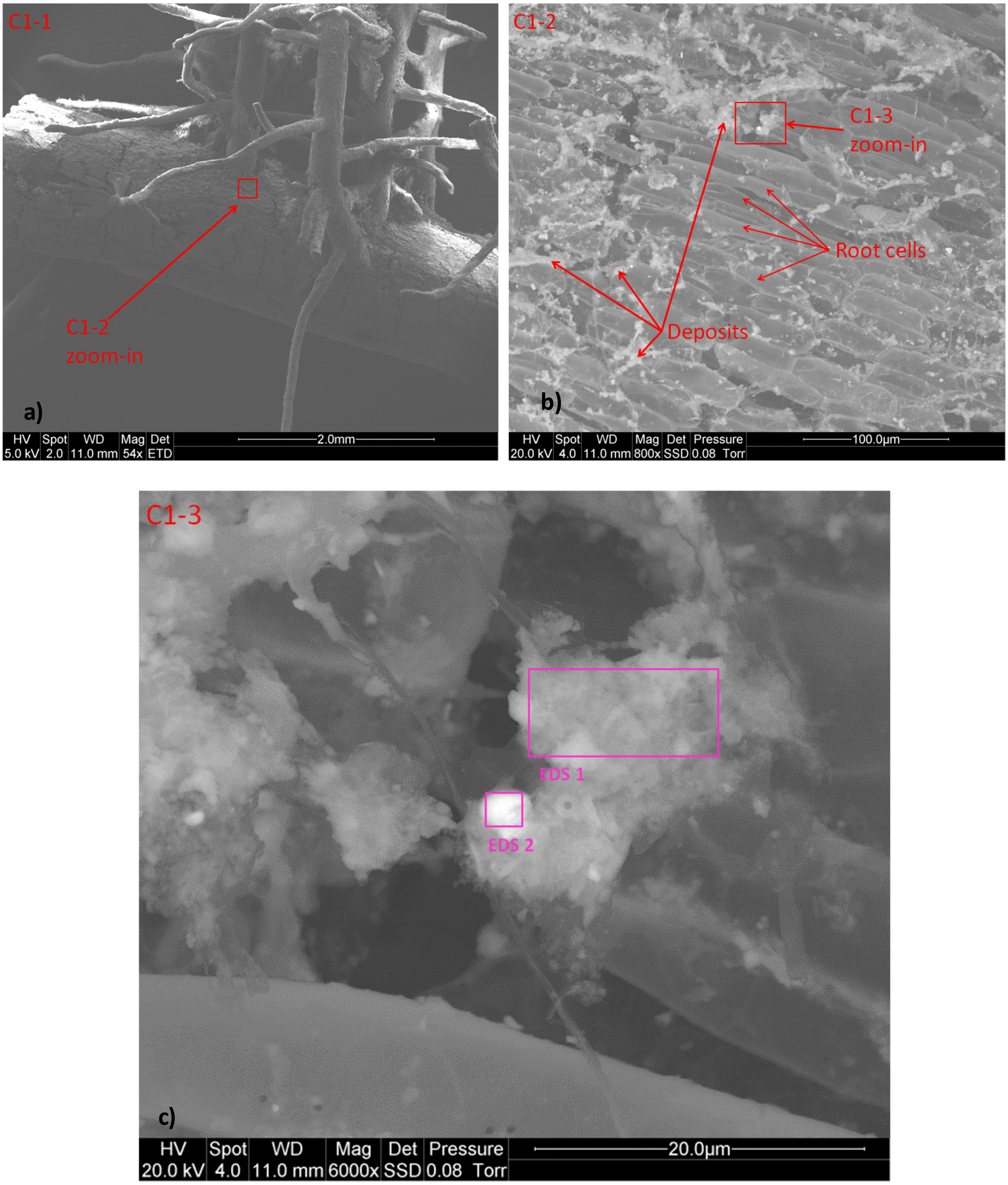


Figure 9: Electron dispersive analysis of root deposit-EDS1. Carbon (C) and oxygen (O) are components of the plant cells.

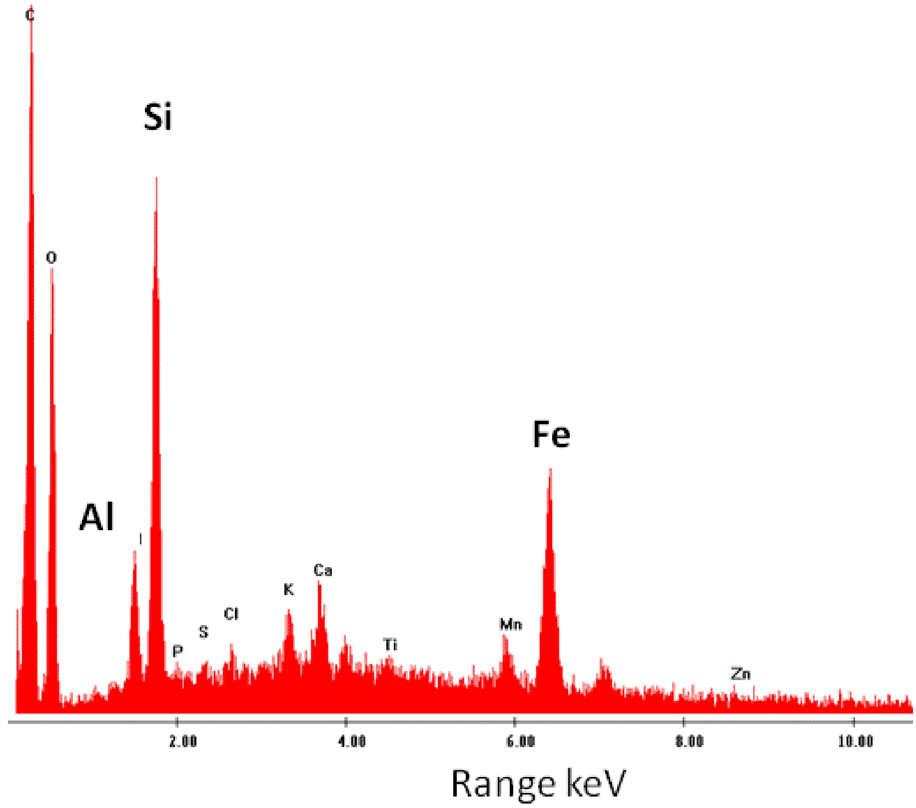
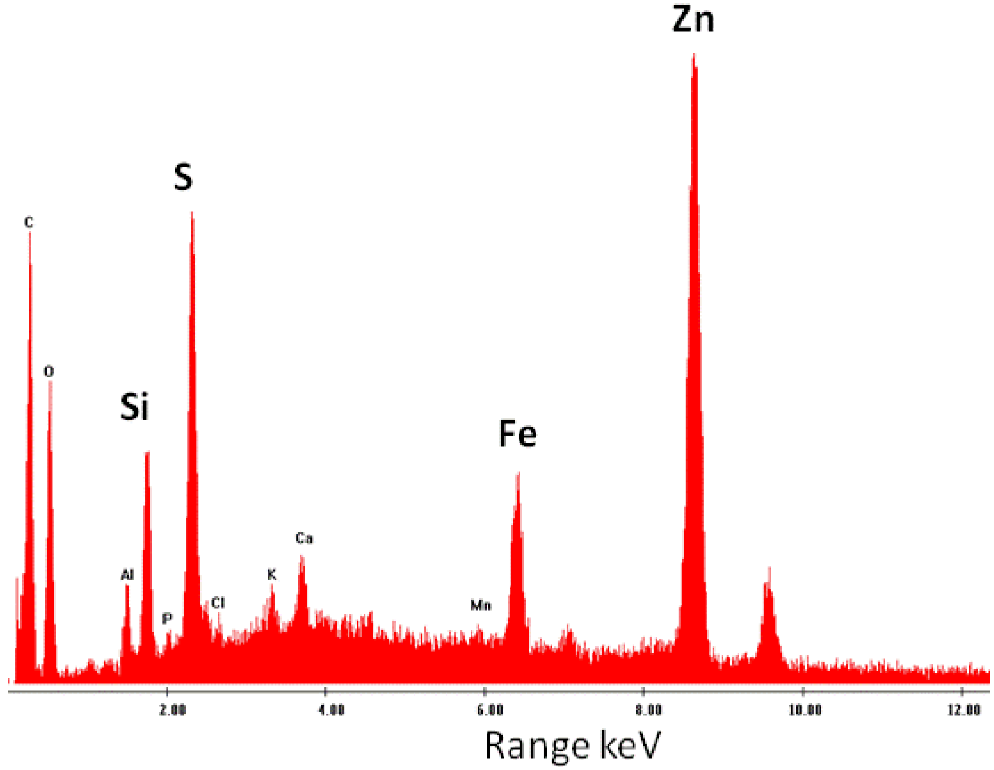


Figure 10: Electron dispersive analysis of root deposit-EDS2. Carbon (C) and oxygen (O) are components of the plant



cells.

3 CONCLUSION

The present research will contribute to the assessment of the global efficiency of a pond retrofit with a FVI compared to a conventional retention pond. Furthermore this study will identify the processes involved in the pollutant removal by a FVI, which are for now unknown. The correlation of the physicochemical parameters induced by a FVI with the different removal pathways will help to establish a relationship between the design of a FVI and the pollutant removal efficiency. This will contribute to design specifically for improved stormwater treatment. Such techniques could thus be more widely implemented for road and urban areas and would contribute to sustainable urban development and landscaping in a cost-effective manner.

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