DEMONSTRATION AT GREENHOUSE

Why this location

For validating the Socorro app (AI model), different demonstration sites were proposed and selected. Most of the sites are maritime environments, where the chloride concentration is key for most of the corrosion phenomena. However, an industry where also a lot of corrosion issues are found, are the wastewater treatment plants.

In WP1, a lab-scale dataset was generated in simulated wastewater. The chloride content and the temperature were two main parameters that were varied. A C-Cube LPR sensor and an Aquaread AP-800 probe were used to generate data. However, the predicted corrosion risk and/or rate should be validated in real demonstration site. Hence, two wastewater treatment plants were proposed: a MBBR installation located at a greenhouse, and one industrial wastewater plant. The benefit of using the MBBR plant is that the working principle is similar to the lab set-up that is being used to train the AI model. Another benefit is that there is already some existing knowledge about the set-up. The MBBR at the greenhouse in Putte (Flanders), is build and operated by co-workers in framework of Interreg project "Nuredrain" (https://northsearegion.eu/nuredrain/). The installation is easy accessible, electrical power supply is already foreseen and high corrosivity is expected due to all the microbiological activities inside the reactor.

Baseline/starting situation

The wastewater treatment installation is located at a greenhouse in Putte (Flanders, Belgium). Tap water is mixed with different fertilizers to maximize plant growth, together with the optimal environment parameters which are well-controlled. The greenhouse in Putte is growing different types of lettuces crops. The water is intensively re-used by the farmers. However, if the water quality is poor (by the presence of bacteria ect.), a part of the water will be drained. Most of the Belgian farmers do not have a wastewater treatment and hence, the wastewater is immediately released into the environment. To avoid problems with eutrophication, the Belgian government introduced a new rule. Wastewater cannot contain more than 50ppm NO_3. Farmers who still exceed those values can be fined if a check is performed at their site. A cost efficient and ecological way to remove excess of nitrate in wastewater is by the implementation of a MBBR; a Moving Biofilm Bed Reactor. As a proof of concept, a scale-up of the labscale MBBR (used for generating data to train to AI model in WP1) was built next to the greenhouse (figure). The MBBR is completely built out of concrete, and is installed below ground level. To make sure that all wastewater has approximately the same residence time, a buffer tank (made out of galvanized steel with black foil) is installed before the MBBR. This ensures that, even though the MBBR has a capacity of only 3m^3 of water per day, higher volumes of wastewater can be treated when spread over a few days (farmer does not send wastewater to the installation each day).

Figure: the MBBR installation next to the greenhouse, in Putte (Flanders).

In framework of Interreg project "Nuredrain", a few engineers/colleagues were already investigating the efficiency of the MBBR (located in Putte) before the official start of Socorro. Before that the wastewater goes into the MBBR, nitrate levels of 1000-1200ppm are measured by IC (Ion Chromatography). Especially when the MBBR is running smoothly (constant inlet of new wastewater), high efficiencies up to 80-95% were noted (figure). Behind the removal of these high nitrate concentrations, there are a few chemical reactions that are being executed by micro-organisms. With the presence of an easy-degradable carbon source (CarboSt, glycerol-based), nitrate-reducing bacteria are able to convert nitrate into nitrogen gas (N_2). This removal is defined as "denitrification", and preferably, these biological reactions (performed by the heterotrophic bacteria) are performed under anoxic conditions (bacteria will consume the excess of oxygen).

$$NO_3^- + 2e^- + 2H^+ \rightarrow NO_2^- + H_2O + energy$$

$$NO_2^- + 3e^- + 4H^+ \rightarrow \frac{1}{2}N_2 + 2H_2O + energy$$

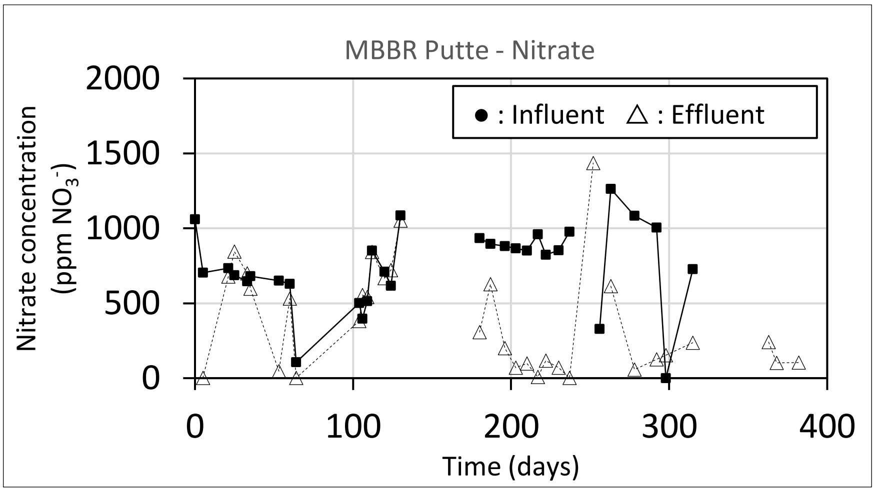


Figure: Nitrate concentration in the wastewater, before and after the MBBR installation.

The chloride concentration in the wastewater is not as high as in other demonstration sites (e.g. canal water, seawater). It (normally) varies between 50-200ppm chloride, and sometimes it peaks to values of 400-450ppm (figure). Even though the chloride concentration is relatively low, it can still be an aggressive environment. Especially if no new wastewater is send to the MBBR, because then, there is the possibility that other micro-organisms (such as Sulfate Reducing Bacteria) are grown by the carbon source (CarboSt). These bacteria are known to result into strong corrosion phenomena/effects that could not only affect the most common steel grades, but also stainless steels.

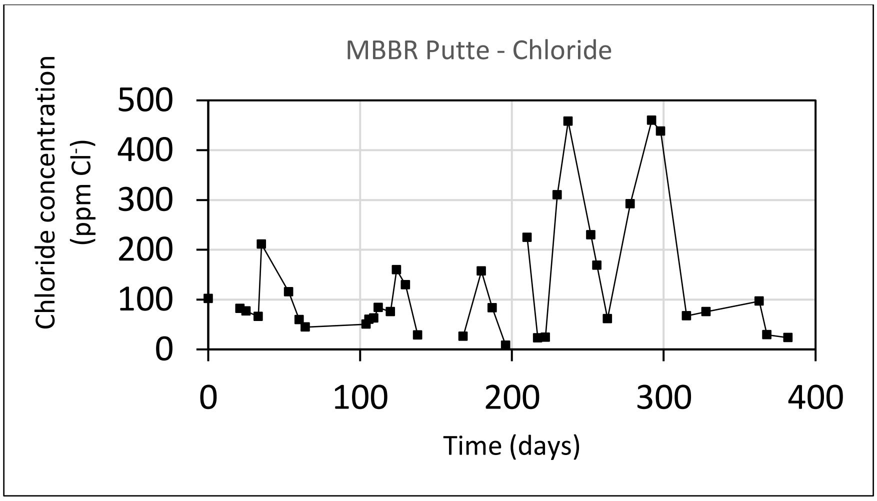


Figure: Chloride concentration in the wastewater, before the inlet of the MBBR installation.

Construction

Inside the MBBR, there are already a few probes that are measuring the water quality: a Hach-Lange chloride probe, an ORP sensor, a level sensor and a flow sensor (that measured how many wastewater was treated). To power all these probes (that are used for the Interreg Nuredrain), electrical connections were already foreseen. Extra power supplies were made to connect two probes for this demonstration site: 1) An Aquaread AP-800 environmental probe (that measures pH, conductivity, temperature, turbidity, salinity, pressure, ...) and 2) a C-Cube probe that continuously measures corrosion rate of S235, S355 steel and an AISI 316L stainless steel by conducting non-destructive LPR measurements. The environmental probe is connected to a Eijkelkamp modem that logs all the water parameters each half an hour. The C-Cube probe measures the corrosion rate each 6h.

Figure 1: The MBBR with the installed C-Cube and Manta probe

To validate the measured corrosion rates of the C-Cube probe, a sample rack with coupons of the 3 grades was also immersed in the MBBR. Within this sample rack, each grade has 4 coupons (per month): 3 coupons are being used for weight loss determination, the last coupon can be used for microscopic analysis. The whole sample rack is made out of plexiglas to avoid any galvanic corrosion effects. After 1, 2, 3 and 6 months, samples were retrieved from the MBBR and corrosion rates are calculated based on their weight loss and the active surface area.

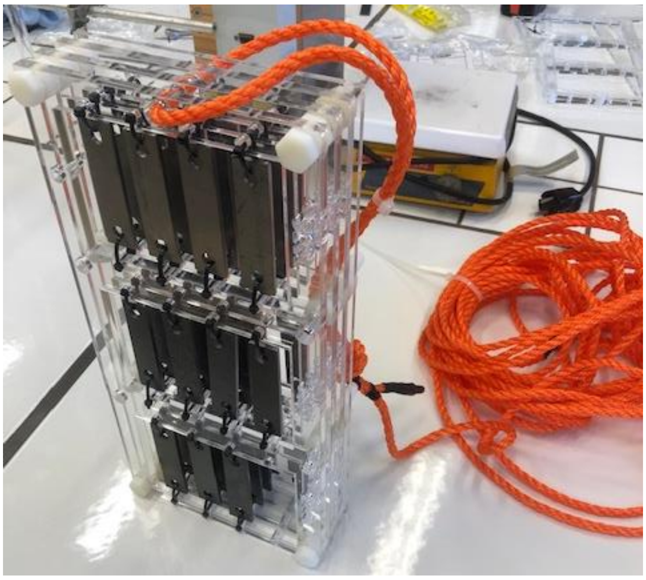


Figure: Sample rack immersed in the MBBR for weight loss determination.

In May 2022, the C-Cube corrosion sensor was installed in the MBBR. The corrosion sensor was checked before its actual use to generate a demonstration dataset, especially because many problems were noticed with the earlier Cosasco® LPR probes (used in the begin of the project). The corrosion sensor was running fine for a few weeks when strong peaks in corrosion rate were suddenly measured. The rates increased to unreasonable values of 25mm/y. When the sensor was checked on site, it was clear what happened (figure). A black sludge was covering the electrodes of the sensor and caused a direct contact between the working electrode and counter electrode, something that cannot happen when measuring the corrosion rate. As good practice and to avoid similar situations, the corrosion sensor and the environmental probe were checked each 1-2 weeks and cleaned when needed to. The chloride, nitrate and sulfate concentration were regularly measured by IC analysis to gain more information about the water quality (and the efficiency of the MBBR).

Figure: The C-Cube sensor after running for a few weeks in the MBBR without maintenance (black sludge covering the electrodes)

Results:

1) Timeplots and boxplots of the environmental parameters

The Aquaread AP-800 is an environmental sensor that contains multiple probes to measure the most commonly used water parameters: temperature (in °C), dissolved oxygen (in mg/L), conductivity (in µS/cm), pH, ORP (in mV) and salinity (in PSU). Each half an hour, all the parameters are measured and logged by an external modem. Every 2-3 weeks, the batteries of the modem are changed to ensure continuous monitoring of all water quality parameters.

The environmental probe was installed the 8th of September 2022. At 10 December 2022, the collected amount of data was sufficient and hence, the environment probe was removed from the MBBR installation. That the environmental probe started measuring in the summer and ended during the winter is clearly visible in the temperature pattern (figure A). In the begin of experiment, the water temperature inside the MBBR was around 19-20°C. Eventually, it decreased to values of 12°C. The dissolved oxygen also shows a remarkable pattern. Initially, high values of 8-9 mg/L were measured (approximately 8mg/L, 90-100% saturation) but decreased fast to a DO content below 1mg/L. To ensure that the environmental probe was measuring accurately, the DO content was checked on-site with an external Hach-Lange® probe. The result was more or less the same, the DO immediately decreased to values below the detection limit of 0.16mg/L. During the whole experiment, co-workers that are focussing on the nitrate removal by the MBBR decided to adapt the aeration. Normally, the aeration was controlled by a timer. Every few hours, the aeration jumped on to mix all wastewater present inside the MBBR. To check whether the nitrate removal under aerobic conditions was as efficient as before (with discontinuous aeration steps, controlled by timer), it was decided at the end of October to remove the timer. The wastewater was aerated the whole time and as a matter a fact, when measuring the DO content, it was still below 1mg/L. The low DO content, even with continuous aeration of wastewater, can be explained by the high microbiological activity inside the MBBR. Nitrate-reducing bacteria are intensively consuming oxygen to convert nitrate into nitrogen gas. Even with continuous aeration, the bacteria are consuming it fast enough to keep the DO content below 1mg/L. The graphs of conductivity and salinity are looking very alike. This can be explained because salinity is a derivative of conductivity. In September 2022, the farmer was regularly sending wastewater to the MBBR installation. Around October, the farmer was switching crops and hence, the amount of wastewater was relatively low. This resulted into a decrease in conductivity, it decreased to values of 3000µS/cm. Approximately at the same time when the conductivity was decreasing, a decrease in ORP was also noticed. For biological wastewater treatment plants, the redox potentials usually varies between -200mV and +200mV. Denitrification in specific only occurs between ORP values of -50mV to +50mV. In September 2022 (start of the experiment), the values are still reasonable for a wastewater treatment plant. After a while (starting from October 2022), however, the ORP decreased to values of -600mV. Such low ORP values are uncommon and are indicating that other (unwanted) side reactions are taking place, like e.g. sulfide formation by sulfate reducing bacteria (SRB's, table). To investigate if the low (measured) ORP was an indication for side reactions, multiple samples were taken from the MBBR installation, distributed over a few weeks. The MBBR installation was mainly built to resolve the high nitrate issue inside the wastewater, it is expected that nitrate is the main element being removed. However, if all nitrate is being removed inside the MBBR (a situation that is possible if no new wastewater is send to the installation), the excess of carbon source can be used to drive side reactions. From the regular sampling, it is clear that if no new waste water flows to the MBBR, SRB's can use the excess of carbon to convert sulfate to sulfide. If this mechanism occurs, the concentration of sulfate in the inlet will be (much) higher than the concentration measured inside the MBBR (figure). To prove that the conversion of sulfate is due to the presence of SRB's inside the MBBR, Sulfate Reducing Bacteria Test Tubes were used. Inside the test tube, a straw coloured medium is present that (sensitively) reacts to the production of hydrogen sulfide (by-product of the SRB mechanism). If blackening occurs within 5 days, there is a high chance that SRB's are present. Samples were taken from the inlet and from wastewater inside the MBBR. Not even after 1 day, blackening occurred in the test tubes where wastewater from the MBBR was added. According to the SRB test tube manual, this insinuates that the wastewater inside the MBBR is highly contaminated by SRB's, which then explains the very low ORP values measured by the Aquaread AP-800.

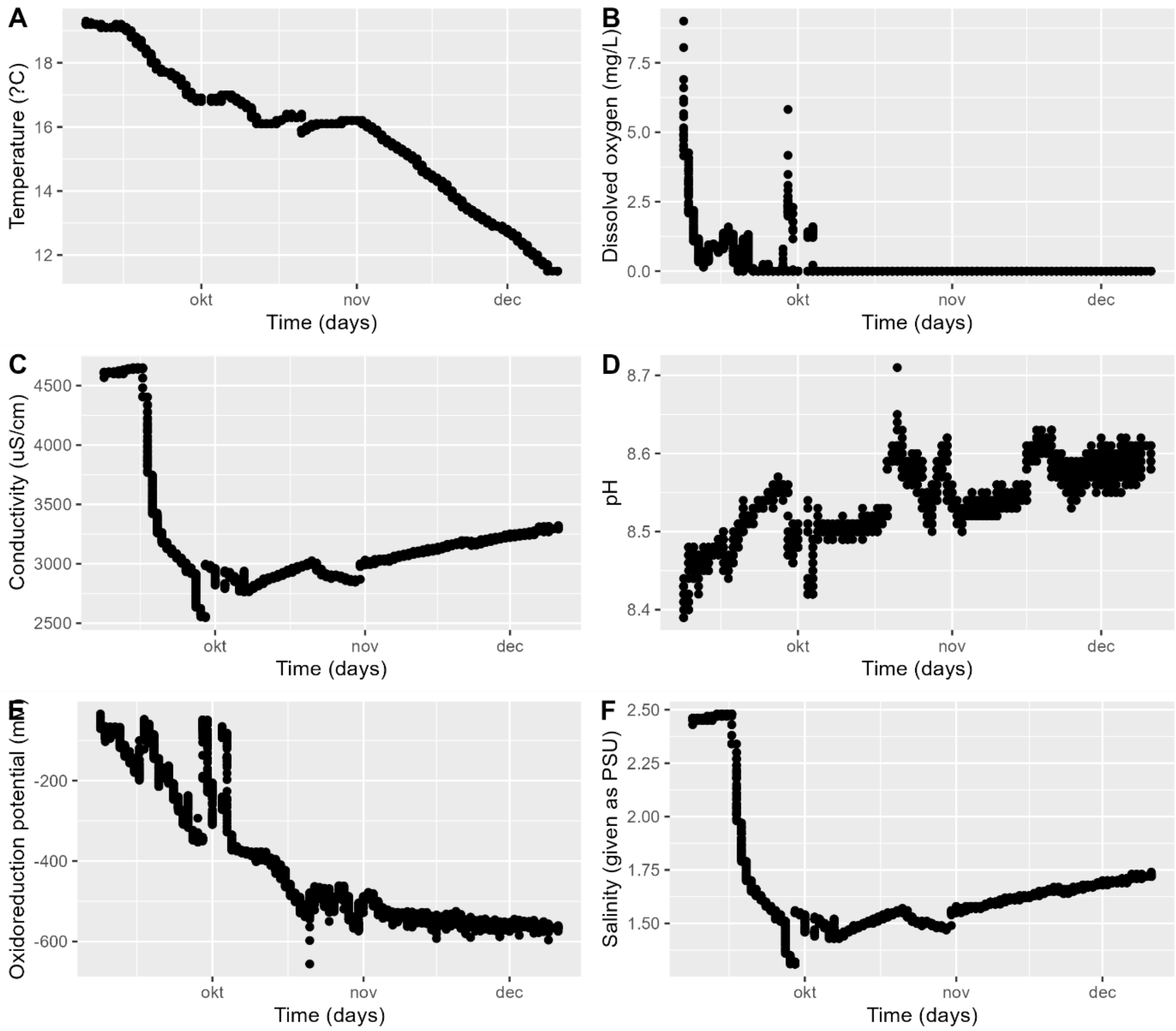


Figure: Overview of the time plots for the MBBR installation in Putte.

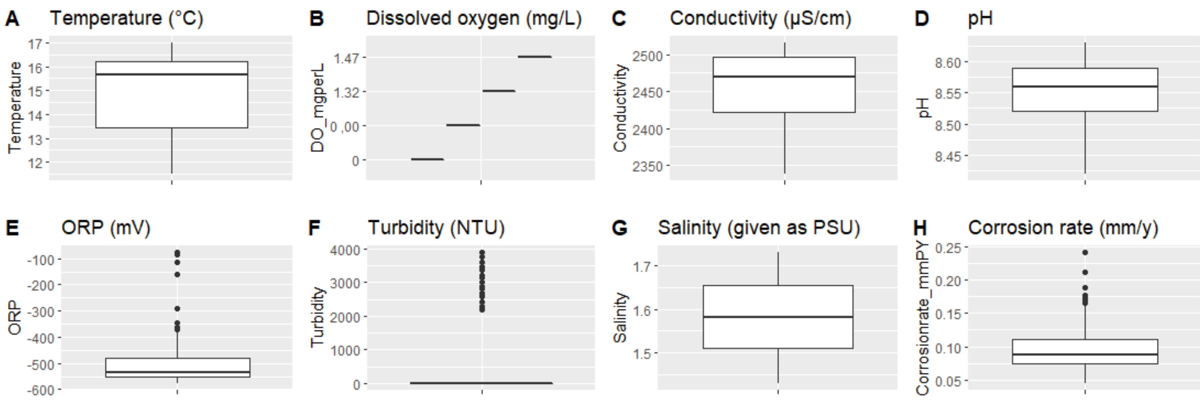


Figure: Boxplots of the environmental and corrosion data in the MBBR installation in Putte.

Table: Biochemical reactions and corresponding ORP values

Biochemical reaction	*ORP (in mV)*
Nitrification	*+100 to +350*
BOD degradation	*+50 to +250*
Biological phosphorus removal	*+25 to +250*
Denitrification	*-50 to +50*
Sulfide formation	*< -250*
Acid fermentation	*< -100*
Methane production	*< -175*

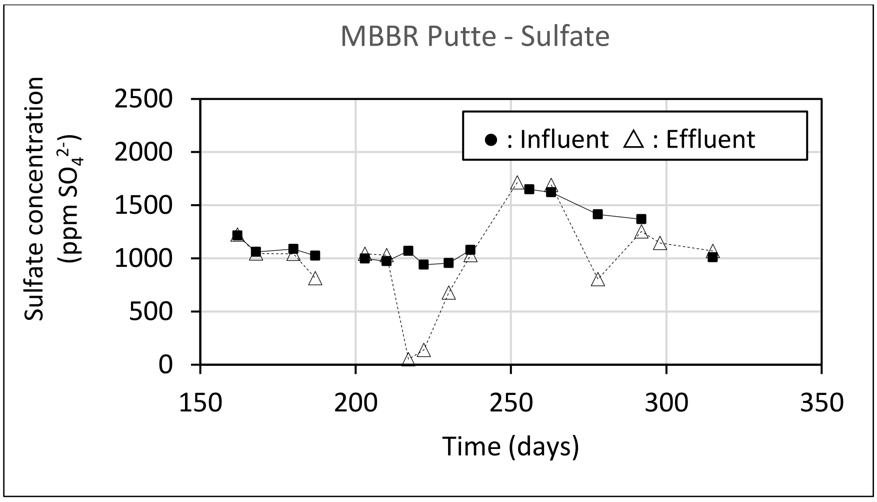


Figure: Sulfate concentration in the wastewater, before and after the MBBR installation.

2) Correlations between environmental parameters

Environmental parameters can also affect each other. As an example, the pH is a temperature-dependent parameter. Salinity is a derivative of conductivity. But are there also correlations between DO, ORP, conductivity, temperature, ...?

A pairwise correlation plot was made with all environmental parameters that were logged inside the MBBR installation. Besides that all effects are presented in a graph, correlation coefficients are also calculated in the correlation matrix. The highest correlation coefficient, being 1, is for the correlation between conductivity and salinity. As mentioned before, the salinity is an immediate derivative of conductivity. Hence, it is not surprising that there is a proportional correlation between both parameters. If the measured conductivity increases, the salinity increases as well. The high value of the correlation coefficient indicates that the correlation between both parameters is very strong (>0.8). A few other strong correlations can be noticed inside the correlation matrix. Between pH and ORP, a correlation coefficient of -0.8 was calculated. The negative sign of the coefficient indicates that the correlation is inversely proportional. If the ORP decreases, the pH increases. Temperature affected the pH and ORP. If the temperature decreases over time, the pH increases. This is something which is also very clear in the time plots (figure). From October to December, the temperature decreased, obviously due to the change of summer to winter. In this same time frame, the pH increased from 8.4 to 8.6 (reversely proportional correlation with temperature) and the ORP decreased from -200mV to -600mV (proportional correlation with temperature). A quite interesting correlation is between the ORP and dissolved oxygen. Between both parameters, a moderate proportional correlation was found. If the DO content decreases, ORP decreases as well, a correlation that is commonly found in biological wastewater treatment plants. Other correlations are rather weak and therefore not statistically significant.

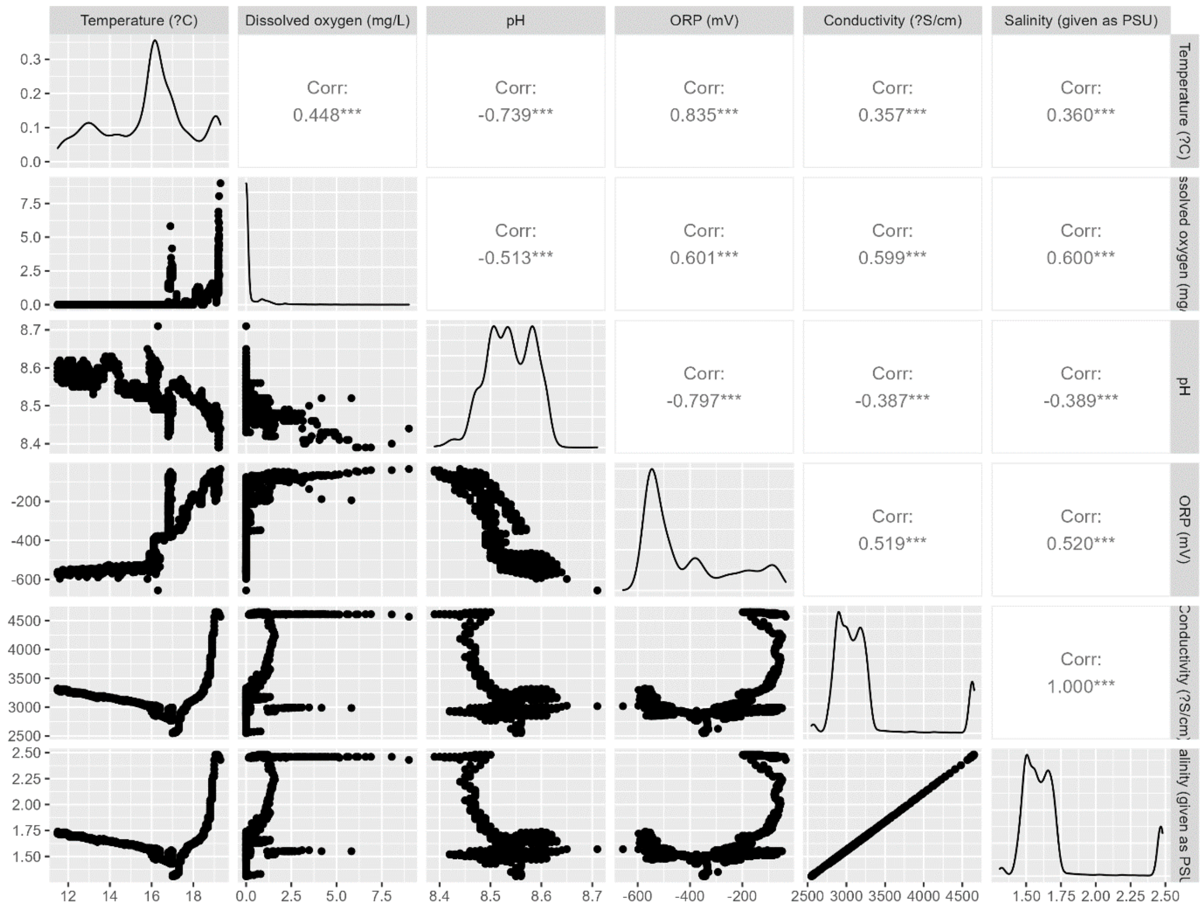


Figure: Pairwise correlation data of the environmental parameters in the MBBR installation

3) Corrosion behavior of S235 steel (grade A) in MBBR installation

The C-Cube LPR probe was used to determine is the corrosion rate of 3 materials: an AISI 316L stainless steel, a S355 steel and a grade A steel. The last steel grade is frequently used in maritime applications: to build sheet piles, to build ships and process equipment,... Although this grade A steel is not as frequently used in wastewater, it is still interesting to investigate how this grade would behave when the chloride content is relatively low but with the presence of more (micro)biological activities. The C-Cube LPR probe works according to a 3-electrode system. The material to investigate (in this case the grade A steel) is the working electrode. By applying small voltages over the working electrode, with the potential differences measure to a stable reference electrode (zinc rod), the electrode is forced to oxidize. The small current that flows due to the oxidation of the working electrode is measured. By the law of Faraday, the corrosion current can be recalculated to a corrosion rate, for steel grades often expressed in mm/y. The salinity of the wastewater didn't exceed values of 2.5 PSU. Hence, we can assume that the water lays somewhere between fresh water (0 PSU) and brackish water (a few PSU). Seawater that is studied intensively in the Socorro project (in the other demonstration sites) should have a salinity around 33-35PSU. Based on the salinity, a low corrosion rate for the steel grade is expected. In figure, the corrosion rate response is plotted in function of time. In the begin, corrosion rates of 0.15-0.2mm/y were measured. After a while, a more stable corrosion response was received, with values between 0.05-0.1mm/y. The reason why the corrosion rate slowly drops in function of time can be explained by the occurrence of corrosion product. In the begin, a bare steel plate acts as working electrode inside the LPR sensor. Without the presence of corrosion product, the steel is "less protective" and hence, higher corrosion rates are measured. After a few months of measuring, a thin layer of corrosion product was noticed on the steel plate. It acts as an extra resistance which results in a lower corrosion rate. Other demonstration sites that are measuring in seawater saw corrosion rates in order of 0.4-0.5mm/y, not surprising considering the higher salinity they have in their environment. Coupons that were immersed in the MBBR were also analyzed for their weight-loss. The weight-loss can be recalculated to a corrosion rate if the dimensions of the original plate are taken into account. After 3-6 months, the weight-loss of the coupons is stable and gives corrosion rate values of ± 0.04mm/y. It can be concluded that the C-Cube LPR sensor gives a corrosion rate in the same order of magnitude. The corrosion rate of the LPR sensor is relatively stable in function of time. Not unexpected considering that the conductivity didn't change intensively inside the MBBR installation.

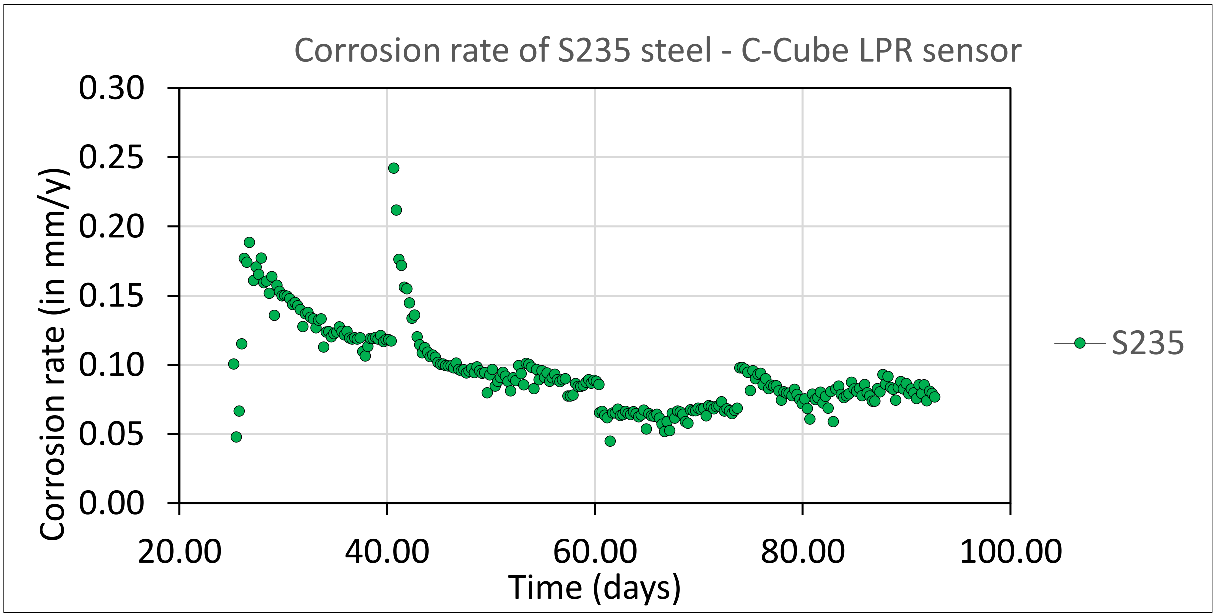


Figure: Corrosion rate of the LPR C-Cube sensor inside the MBBR installation – Putte (Greenhouse)

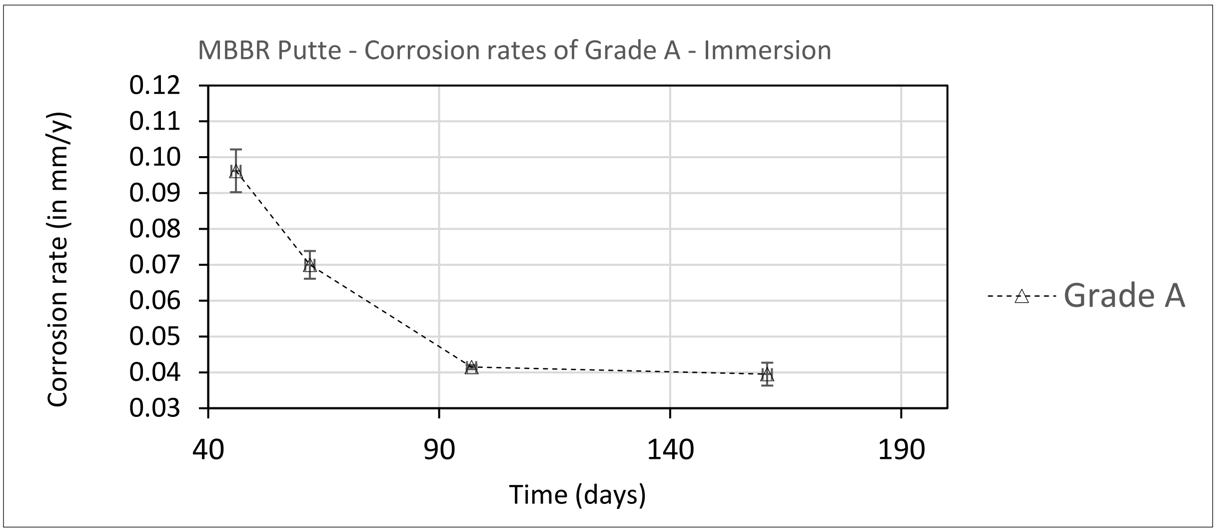


Figure: Corrosion rate of Grade A steel by weight-loss determination of immersed coupons – MBBR Putte (Greenhouse)

The correlation between the corrosion of the C-Cube LPR probe and the related environmental parameters were checked by a Pearson test. The statistical test returns a p-value and a correlation coefficient, the last coefficient being similar to the values calculated by the correlation matrix of figure. 4 parameters had a correlation with the corrosion rate that returned a p-value above 0.05. This insinuates that the correlation found with the pearson test are statistically not significant. Hence, it is concluded that the turbidity, pressure, pH and DO do not affect the corrosion rate significantly. One major remark is that the studied range of the environmental parameters should be taken into account. In literature, many researchers found that pH does affect the corrosion rate. Even a Pourbaix diagram, a thermodynamical way to look at corrosion, shows that the pH of the studied environment strongly affects the corrosion products being formed on the surface. However, within the studied range of the pH (8.4-8.6), no strong affect is noticed. Same remark goes for the pressure, the turbidity and the DO content. For the Total Dissolved Solids (TDS), Conductivity, Salinity and Seawater Specific Gravity (SSG), a reversely proportional correlation with corrosion rate was found. TDS, Salinity and SSG are all parameters that are calculated within the sensor (and its software). It is all derived from the conductivity, and therefore, it is not surprising that their effect on the corrosion rate is similar. That the correlation between conductivity and corrosion rate is found to be reversely proportional, is still somewhat surprising. More conductivity (in general) means that there are more salts present in the wastewater, and normally more corrosion is expected. The different salts present in the wastewater should be distinguished from each other. In figures, it can be noticed that the nitrate, sulfate and chloride concentration are not stable. If the increase of conductivity comes from sulfate, it is indeed possible that this results in a decrease of the corrosion rate as sulfates are known to cause competitional adsorption at the surface together with chlorides. The more sulfate present in the water, the lower the amount of chlorides that can reach the steel surface (which then lowers the corrosion rate). Temperature was found to be proportionally correlated to the corrosion rate of steel grade A. A higher temperature will result into faster corrosion phenomena. Why a higher resistivity and a higher ORP results into a higher corrosion rate is still unclear and should be studied in future work.

Table: Correlation between the corrosion rate (measured by the C-Cube LPR sensor) and the environmental parameters.

Parameter	p-value	Pearson coefficient
~~Turbidity~~	~~0.986~~	~~0.0014~~
~~Pressure~~	~~0.85~~	~~-0.015~~
~~pH~~	~~0.05102~~	~~-0.16~~
~~DO~~	~~NA~~	~~NA~~
Total Dissolved Solids	$4.5*10^{-11}$	-0.50
Conductivity	$4.5*10^{-11}$	-0.50
Salinity	$4.6*10^{-11}$	-0.50
Seawater Specific Gravity	$6.3*10^{-8}$	-0.42
Temperature	$2*10^{-6}$	0.37
Resistivity	$1.4*10^{-9}$	0.46
ORP	$5.5*10^{-16}$	0.59

Another way to look at correlation is by a Principal Component Analysis (abbreviated as PCA). A PCA reduces the dimensionality of large datasets by converting a large set of variables (environmental parameters + corrosion rate) to a smaller set (principal components) that still contains the most important information. In figure, a Screeplot was made with the data that was collected from the MBBR installation. It is clear that the two first principal components (PC1 and PC2) can explain more than 80% of the total variance seen in the original dataset. If PC3 is additionally included, more than 90% of the variance is included. PC1, PC2 and PC3 are used to generate a PCA plot. A PCA plot is a biplot with two principal components on the X- and Y-axis. All datapoints with their environmental parameters and corrosion rate are plotted on this new dimensional plot. Based on the values of the variables, different clusters with similar environmental parameters and/or corrosion rate can be defined. The PCA software draws vectors for all clusters based on their environmental parameter values. In the PCA plot (figure, lay-out FactoMineR), all arrows/vectors are representing 1 environmental parameter. If 2 vectors are laying close to each other (same direction + same sense), that means that a cluster was found were both environmental parameters are alike, hence, it is suggested that they are correlated. If two vectors have the same direction but the sense is different (arrows are pointing to a different side), a reversely proportional correlation is found. If the arrows are not close to each other and are making an angle of approximately 90°, this insinuates that, on the new dimensional biplot, no cluster were found were both parameters were variating is in similar way. Hence, no correlation is expected between both parameters. The vector of corrosion rate (of grade A) lays close to the vector of ORP and resistivity. This is in agreement with the correlations found in table, where resistivity (inverse of conductivity) and ORP were found to be correlated to the measured corrosion rate. The vector "temperature" is not laying close to the vector of corrosion rate. Thus, the PCA analysis concludes that no (strong) correlation is found. Not in complete agreement with the findings of table, but still, temperature had the weakest proportional correlation with the corrosion rate (lowest correlation coefficient). Vectors "SSG", "Conductivity", "TDS" and "salinity" are laying close to each other. This makes sense, as these variables are all derived from the measured conductivity. The vectors make an angle of approximately 60° with vector "corrosion rate". It is therefore concluded that the correlation is not strong. The vector have a different sense, this means that the correlation is reversely proportional. A moderate reversely correlation was suggested by the outcome of the Pearson correlation tests (table), this is consistent with the result of the PCA biplot.

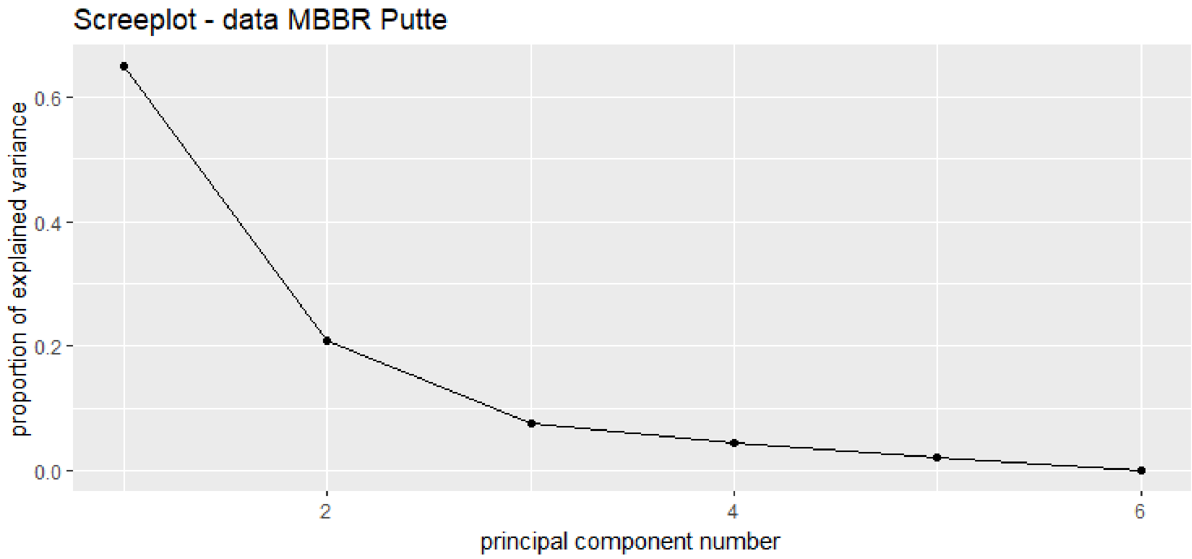


Figure: Scree plot of the principal components – MBBR Putte

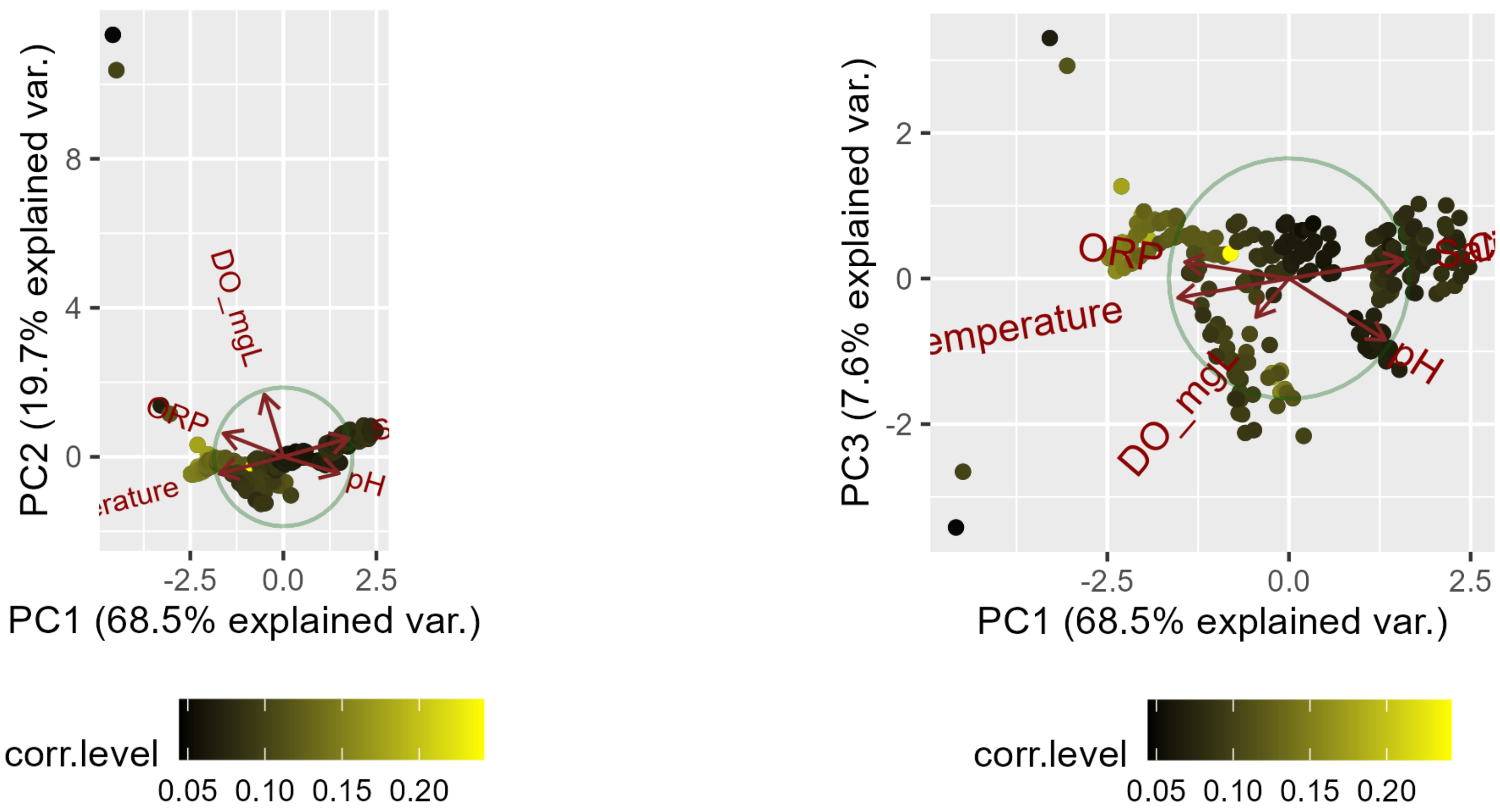


Figure: PCA plots of PC1/PC2 (left) and PC1/PC3 (right) – MBBR Putte

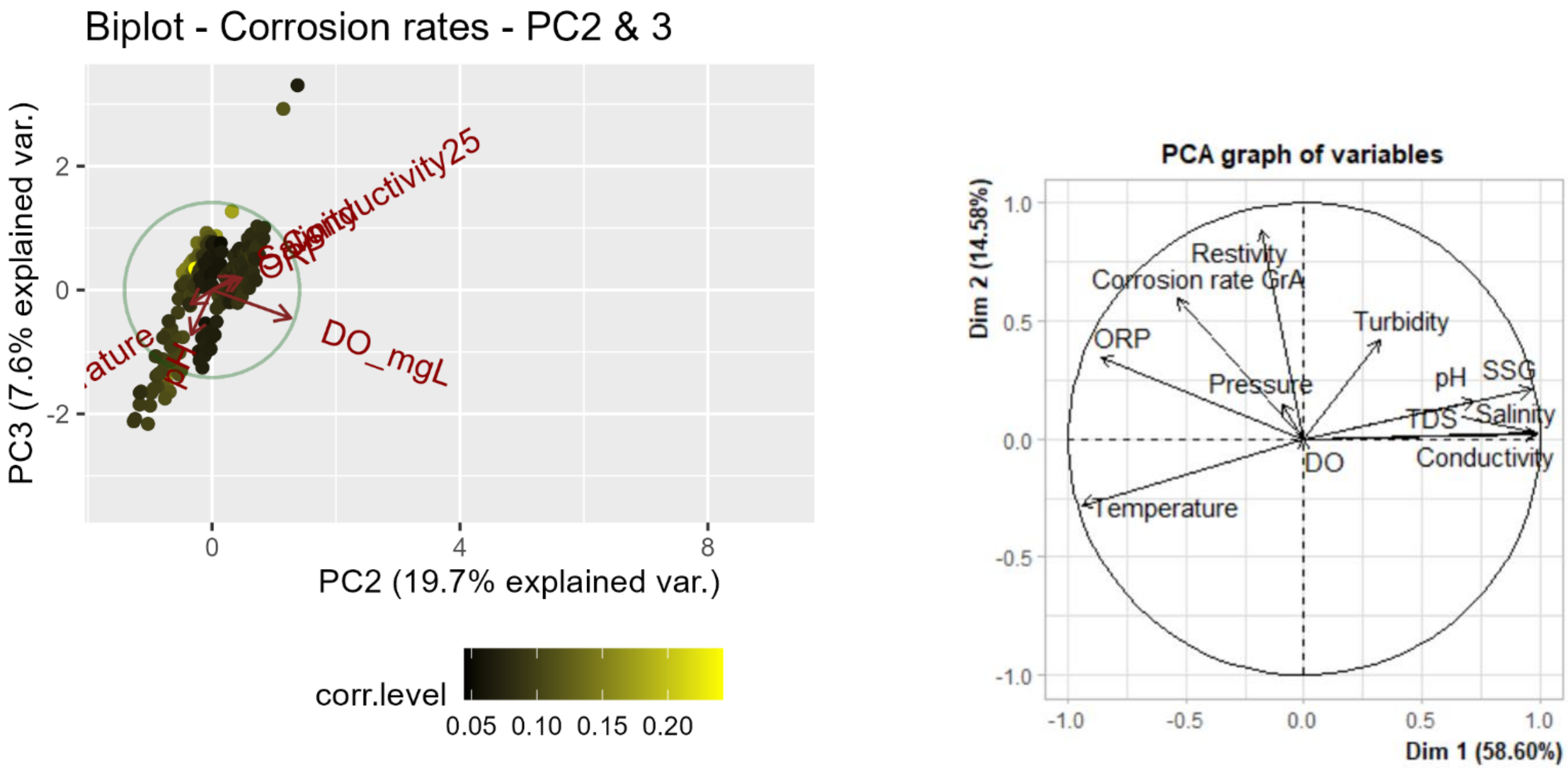


Figure: PCA plots of PC2/PC3 (left) and PC1/PC2 FactoMineR package (right) – MBBR Putte

4) Corrosion behavior of S355 steel in MBBR installation

Next to the S235 steel (grade A), the C-Cube LPR sensor also contains a S355 steel. The chemical composition of this steel type is very similar to the S235 steel, however, the main difference between both grades in mechanical properties. The S235 steel has a tensile strength of 235MPa, the S355 steel has a higher tensile strength of 355MPa making it more interesting to use in steel constructions. In WP3, the S355 steel is compared to a S235 steel in a LCA and LCAA analysis. To guarantee the same mechanical properties, less S355 material should be used than S235 steel making it also more interesting from an economical point of view. The S355 steel was also investigated on its corrosion behavior inside the MBBR installation. The corrosion rate started on values of approximately 0.3mm/y. Same explanation applies for this steel grade. The S355 sensor does not have any corrosion product in the begin of the test, hence the higher corrosion rates. After a while, a stable corrosion product is formed which causes a decrease in corrosion rate. The corrosion starts to stabilize around values of 0.11-0.15mm/y, which is slightly higher than the corrosion rate found for S235 steel (0.05-0.1mm/y). This is in agreement with the partners (AMA, Sirris) that measured on other demonstration sites. The S355 steel consistently showed a higher corrosion rate compared to the S235 steel. Looking to their chemical composition, this should not be the case. When looking the sensor after being installed in the MBBR for 6 months, there was, besides the difference is corrosion rate, also a difference is corrosion attack. While the S235 electrode looked highly affected by uniform corrosion, it was surprising to see that the S355 electrode of the C-Cube probe also showed local attack (presence of pits). Perhaps this explains why higher electrochemical rates were calculated by the LPR fitting for the S355 steel.

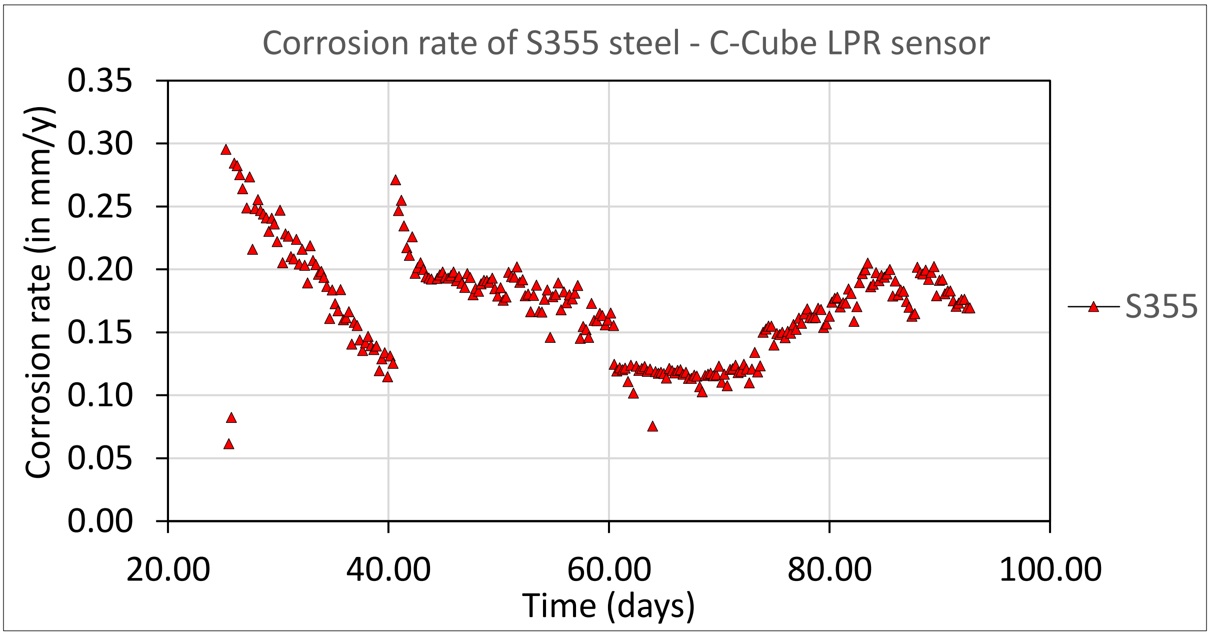


Figure: Corrosion rate of the LPR C-Cube sensor inside the MBBR installation – Putte (Greenhouse)

Figure: Local corrosion attack (pits) on the S355 working electrode of the C-Cube LPR probe after 6 months of installation in the MBBR installation – Putte (Greenhouse)

Figure shows the corrosion rates of the S355 coupons determined by weight-loss. The coupons were cleaned according to the ASTM G31 standard. From the long-term immersion tests, that were analyzed after 1,2,3 and 6 months, it is clear that the corrosion rate of the S355 steel is not significantly higher than S235. The corrosion rate of the S355 stabilizes after 3-6 months to a value of ± 0.04mm/y. The inconsistency of the S355 corrosion data received from the LPR sensor and the corrosion rates from weight-loss determination should be discussed in further detail with manufacturer C-Cube.

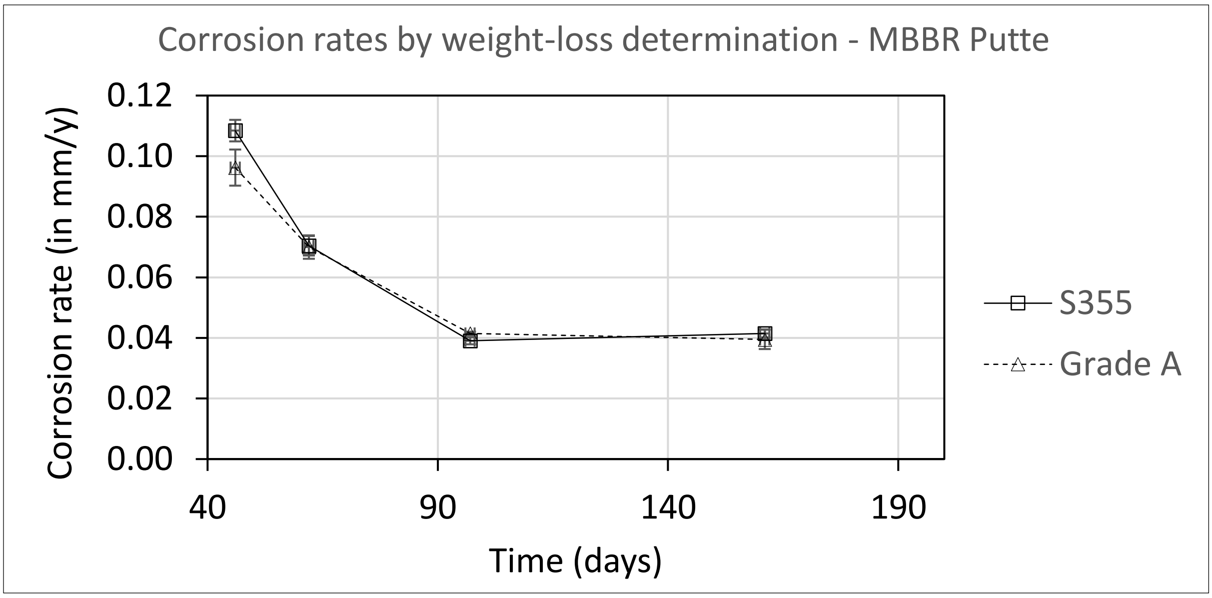


Figure: Corrosion rate of S355 steel by weight-loss determination of immersed coupons – MBBR Putte (Greenhouse)

Correlations between the corrosion rate (measured by the C-Cube LPR probe) and the environmental parameters are again checked by a Pearson correlation test. It is remarkable that the amount of significant correlations is lower compared to the S235 data. Temperature shows a reversely proportional correlation with the measured corrosion data for S355 steel. The p-value (<0.05) shows that the correlation is statistically significant. However, the low correlation coefficient (i.e. -0.16) implies that the found correlation is rather weak. Normally, a proportional correlation is expected between temperature and the measured corrosion data. This is an import issue that should be checked by future research. The pressure, turbidity, ORP and resistivity show a proportional correlation with the corrosion rate of S355 steel. If those environmental parameters increase, the corrosion rates increases as well. For turbidity, this can be expected. Contaminated water often contains more aggressive species and hence, more corrosion is expected. A higher ORP indicates a more oxidative environment also this could lead to a higher corrosion rate. However, a proportional correlation between resistivity (inverse of conductivity) and the corrosion rate is rather strange and should be checked in further detail.

Table: Correlation between the corrosion rate (measured by the C-Cube LPR sensor) and the environmental parameters.

Parameter	p-value	Pearson coefficient
~~DO~~	~~NA~~	~~NA~~
Temperature	0.043	-0.16
~~Conductivity~~	~~0.88~~	~~0.012~~
~~Salinity~~	~~0.89~~	~~0.012~~
~~Total Dissolved Solids~~	~~0.88~~	~~0.012~~
~~pH~~	~~0.29~~	~~0.08~~
~~Seawater Specific Gravity~~	~~0.19~~	~~0.11~~
Pressure	0.02	0.18
Turbidity	0.017	0.19
ORP	0.01	0.20
Restivity	$4.3*10^{-13}$	0.54

The corrosion data and the environmental variables were further investigated by a PCA analysis. Vectors "Corrosion rate" shows a similar direction and sense to environmental parameters "Pressure" and "Resistivity". This means that high corrosion values are often associated with an environment that contained a higher resistivity (or a lower conductivity) and a higher pressure. Both parameters also showed a proportional correlation in the Pearson test (Table). The corrosion rate in the PCA does not show a (strong) correlation with the ORP and turbidity. Vector "pH", "Salinity", "Conductivity", "DO", "TDS" and "Seawater Specific Gravity (SSG)" make an angle of almost 90° with vector "Corrosion rate" and therefore, no correlation is expected according to the PCA. This is in line with the outcome of the Pearson test.

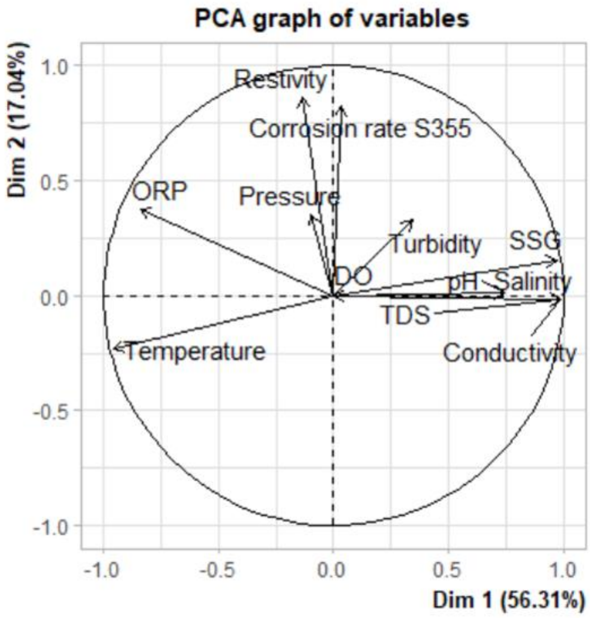


Figure: PCA plots of PC1/PC2 – FactoMineR package – MBBR Putte

5) Corrosion behavior of AISI 316L in MBBR installation

The most corrosion resistant material inside the C-Cube LPR probe is the AISI 316L. This austenitic stainless steel contains 10-12% of nickel as austenite stabilizer, 16-18% of chromium to improve its corrosion resistance, 2-3% to increase the pitting resistance in chloride-rich media and a lower carbon content to improve weldability (and its corrosion behavior after welding). The AISI 316L is commonly used for wastewater treatment plants, to build storage tanks, pipelines and process equipment. Because the AISI 316L is widely investigated in chloride-containing environments, most of the manufacturers of wastewater treatment installations consider it as a safe choice to ensure corrosion resistance and to guarantee its designed life time. Because MBBR installations are still investigated by many research institutes and the existing installations are relatively small (capacity of a few m^3/day), the flow of wastewater and pressure inside such installations are limited. Because there is no necessity to use steel grades, because the pressure and flow is low, most of these installations are build out of concrete with PVC piping. This is also interesting to lower the installation costs, high costs for a wastewater treatment plant are often not feasible for a greenhouse/farmer like in Putte (Flanders). Still, it would be interesting to see how the AISI 316L performs in a wastewater with a lot of microbiological activity. Every 6 hours, the corrosion rate of stainless steel in logged. In figure, it is convenient that the AISI 316L material is more corrosion resistant as the found corrosion rates are expressed in µm/y instead of mm/y (for steel grades). Corrosion rates as low as $3.9*10^{-38}$ µm/y were found by the LPR fitting. Maximum values go up to 12µm/y. It should be emphasized that measured corrosion rates lower than 0.1µm/y are not realistic. C-Cube LPR sensors with their electrical properties are normally not able to measure corrosion rates lower than 0.01µm/y. If such low corrosion rates need to measured accurately, the electrochemical equipment should be able to measure a corrosion current of $1nA/cm^2$ accurately. These corrosion currents are only measurable when using a faraday cage (like used in lab set-up), and not for electrochemical sensors for in-situ use. In figure, it is clear that both steel plates had issues with corrosion product being formed while the AISI 316L remained unaffected (besides some dirt). The corrosion rates determined by weight-loss are also not giving more information than the sensor. The weight-loss after 6 months is still lower than 0.0001g per coupon. This means that if a corrosion rate is calculated for the AISI 316L coupons, the corrosion rate in theory returns a zero value (no corrosion occurred). However, taking into account the accuracy of the analytical balance, it is assumed that the corrosion rates of all AISI 316L coupons are lower than 0.03µm/y.

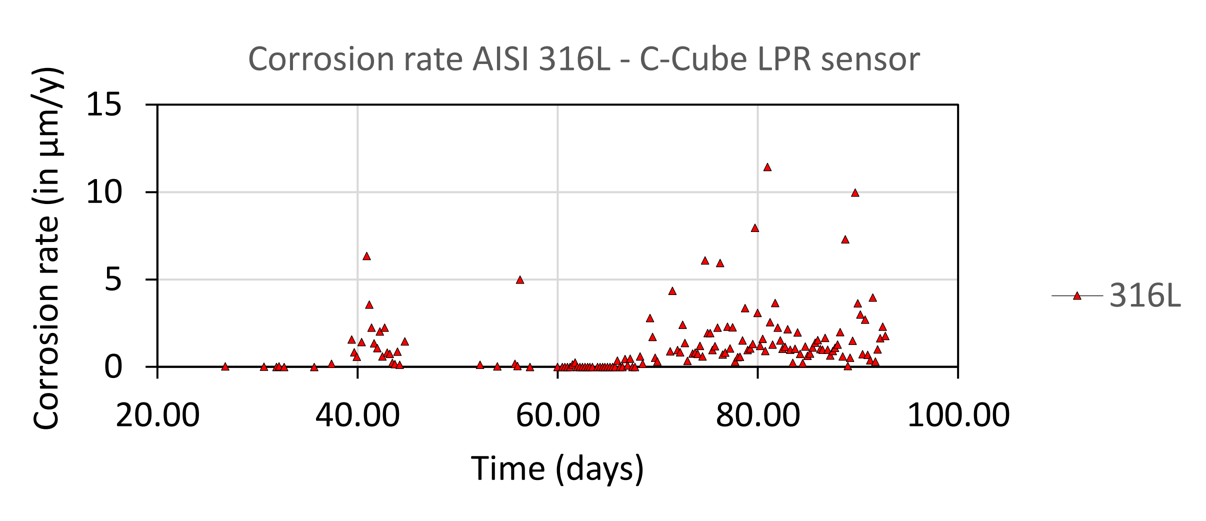


Figure: Corrosion rate of the LPR C-Cube sensor inside the MBBR installation – Putte (Greenhouse)

Because the C-Cube LPR sensor was not able to determine the corrosion rate of AISI 316L accurately, found correlations should be interpreted with caution. All the found correlations should be checked in a lab-scale environment with a more accurate electrochemical set-up. Hence, the found correlations of the Pearson test and the PCA analysis are not discussed in detail.

Table: Correlation between the corrosion rate (measured by the C-Cube LPR sensor) and the environmental parameters.

Parameter	p-value	Pearson coefficient
~~DO~~	~~NA~~	~~NA~~
Temperature	0.0006	-0.30
ORP	0.013	-0.22
~~Pressure~~	~~0.051~~	~~-0.17~~
~~Resistivity~~	~~0.5~~	~~0.06~~
Turbidity	0.013	0.22
Salinity	0.002	0.27
Total Dissolved Solids	0.002	0.27
Conductivity	0.002	0.272
Seawater Specific Gravity	0.0009	0.29
pH	$4.76*10^{-5}$	0.35

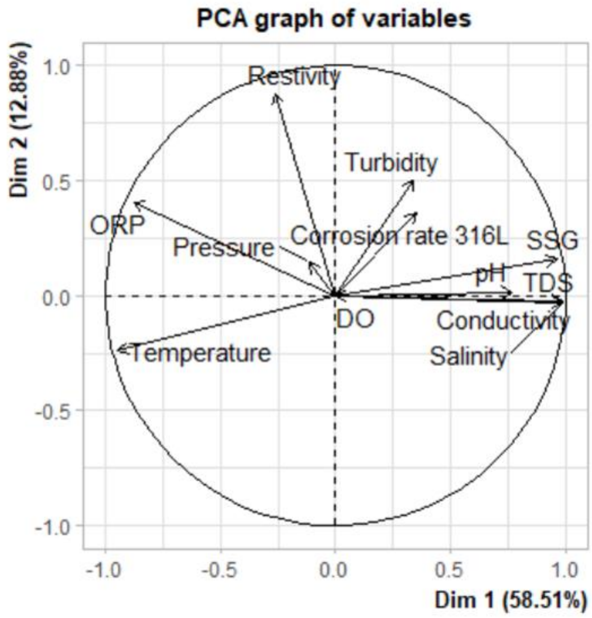
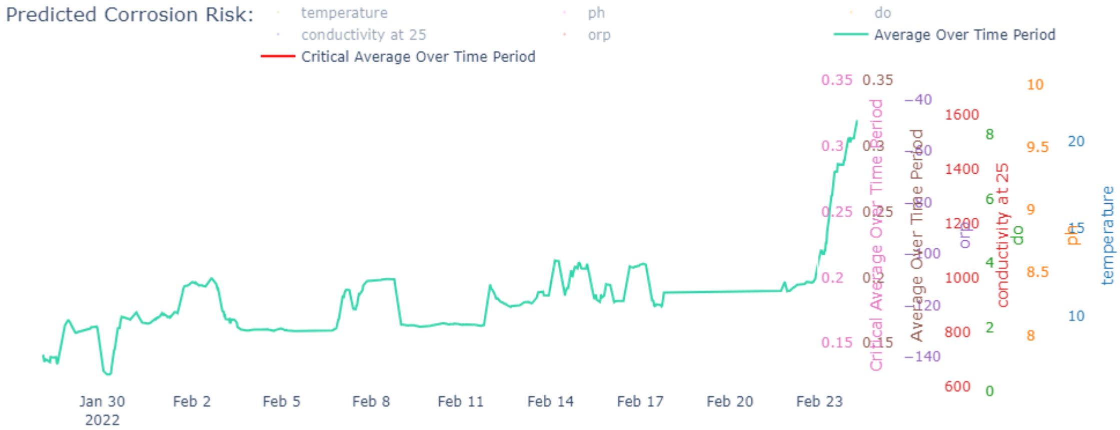
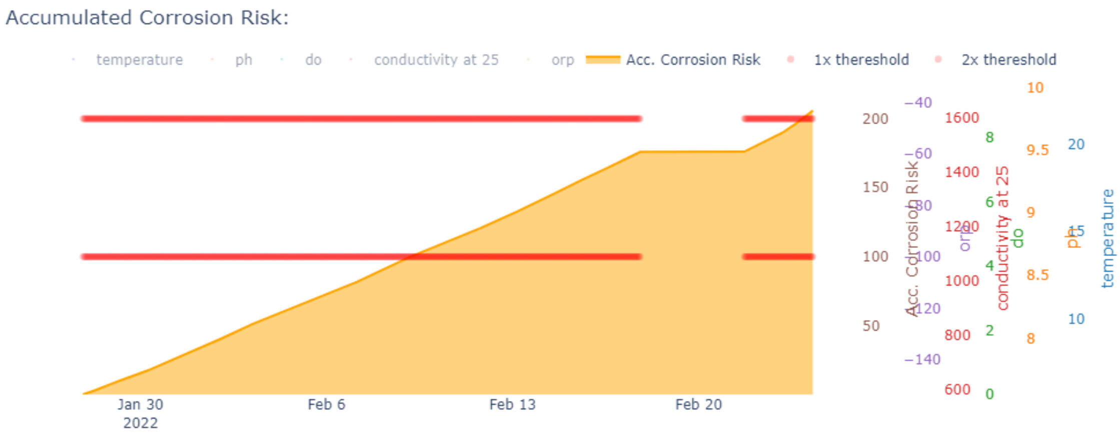


Figure: PCA plots of PC1/PC2 – FactoMineR package – MBBR Putte

6) Data analysis with the Socorro app





Plans for further use?

The environmental and C-Cube sensor were removed from the MBBR on the 10th of December 2022. Both probes were used to generate a better (and more improved) dataset (on lab-scale, WP1) to train to AI model for corrosion risk assessments in wastewater treatment plants.