RFID technology as cost-effective real-time process monitoring and control tool in continuous sand filters: two case studies

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Abstract

The legislative norms for treated wastewater discharge in terms of nitrogen (N) and phosphorus (P) concentrations are becoming increasingly stringent in the EU region. Compliance with the consent values compelled the water authorities to implement moving bed biofilters (MBFs) for tertiary stage effluent polishing. However, on-site and field surveys reveal that numerous MBF units suffer from non-optimal operational conditions, logistical challenges and irregular monitoring. This makes meeting the consents quite a challenging and expensive affair. It is therefore important to optimize day-to-day operations, facilitate access to reliable and real-time status updates, and troubleshoot the failures. In this direction, an "internet-of-things", radio frequency ID (RFID) and cloud based monitoring and control tool, *Sand-Cycle*, was successfully developed, tested and implemented to monitor MBFs. The current study presents full-scale application of the developed remote control and mote technology at two wastewater treatment works. *Sand-Cycle* illustrated real-time dashboards indicating performance grading factors viz. in-situ average sand circulation rate, active bed volume and filter homogeneity. This presented clear instructions for detected malfunctions and enabled the operators to optimize the MBF output with limited effort. Further technical and technological advancements of such IoT based setups can actively assist in tackling long-term sustainability and wastewater management issues.

Keywords: data analytics, real-time monitoring, moving bed biofilters, remote control, RFID, *Sand-Cycle*

1. Introduction

The practical applicability of Radio Frequency IDentification (RFID) as an identification mechanism dates back to the years of the second world war (1939-1945) to differentiate Friend or Foe (IFF) military aircrafts [1]. The working principle includes an identification process which is activated by wireless communication between a tag attached to an entity and an antenna via radiofrequency waves. The wi-fi transmission is translated into data points which is further analysed to map the activity/identity of the entity. At present, RFID technology found over 3,000 applications and has been heavily used for logistics, supply chain management and quick response systems [2]. Active academic and technical research aimed at construction, data security, reliability of the tags and economics is being performed to further diversify its functionality [3]. Such techno-academic advancements have opened up several avenues for active collaboration with data analytics and fast data management to extend its service from simple inventory tracking to other applications. Water and wastewater industry offers to be the latest and promising domain for RFID utility expansion. The EU guidelines laid by Water Framework Directive (WFD) also assert the necessity to include tools for effective data management in order to achieve reliable wastewater treatment performance [4]. Such tools can ensure efficient and reliable plant performance thereby improving water quality and reducing operational and maintenance costs. Specially, use of passive LF RFID tags operating at low frequency (125-134 kHz) in (waste)water systems is a favourable option as they show minimal interference with metals and liquids [2]. These tags are characterized by their battery-less construction, lower power consumption and their penetration ability through non-metal objects within one foot range. They typically obtain energy from the signal transmitted by the antenna making them maintenance-free and user-friendly.

As a pioneering approach, RFID-based smart monitoring tool, *Sand-Cycle* (www.sand-cycle.com), using passive LF tags, internet-of-things and cloud-based storage platform was introduced into wastewater treatment [5]. Continuous moving bed biofilters (MBFs) were chosen as an initial reference among the available wastewater treatment technologies for developing and testing the integrated RFID framework. MBFs are single reactor based wastewater effluent polishing systems implemented for simultaneous N-P removal in domestic wastewater and industrial (paper and pulp, chemical, steel, food, mining and mineral) wastewater treatment facilities [6]. They work on the principle of (bio)filtration, uninterrupted and homogeneous sand circulation of a filter bed with help of an airlift to remove pollutants and excess biomass (Fig.1a). The filtration process occurs through retaining of pollutants within the pores of the filter bed and possible biological degradation (nitrification/denitrification). The filter bed constantly moves downwards with fixed rate (typically 0.3 – 0.8 m/h) and the treated water flows in upward direction through the moving bed. This counter-current activity between water and sand ensures better treatment efficiency and effluent quality. But, the downward movement of sand, its distribution and actual sand circulation rate are often prone to deviations affecting the filtration efficiency. Field surveys reveal that numerous MBF units operate at arbitrary circulation speeds and suffer from non-optimal operational conditions. They require every day monitoring to meet the stringent discharge limits, overcome malfunctions and reduce downtime. *Sand-Cycle* functions as a continuous monitoring and control tool to provide real-time status updates and support MBF optimization by mimicking the sand movement with the help of LF tags. The key elements of the developed tool include LF tags (transponders) with transmission frequency of 128 kHz, remote sensing, cloud storage, fast data analysis and expert judgement. The tags typically consist of a copper coil that is hermetically sealed in a bio-glass case designed to survive harsh environmental conditions (Figure 1b).

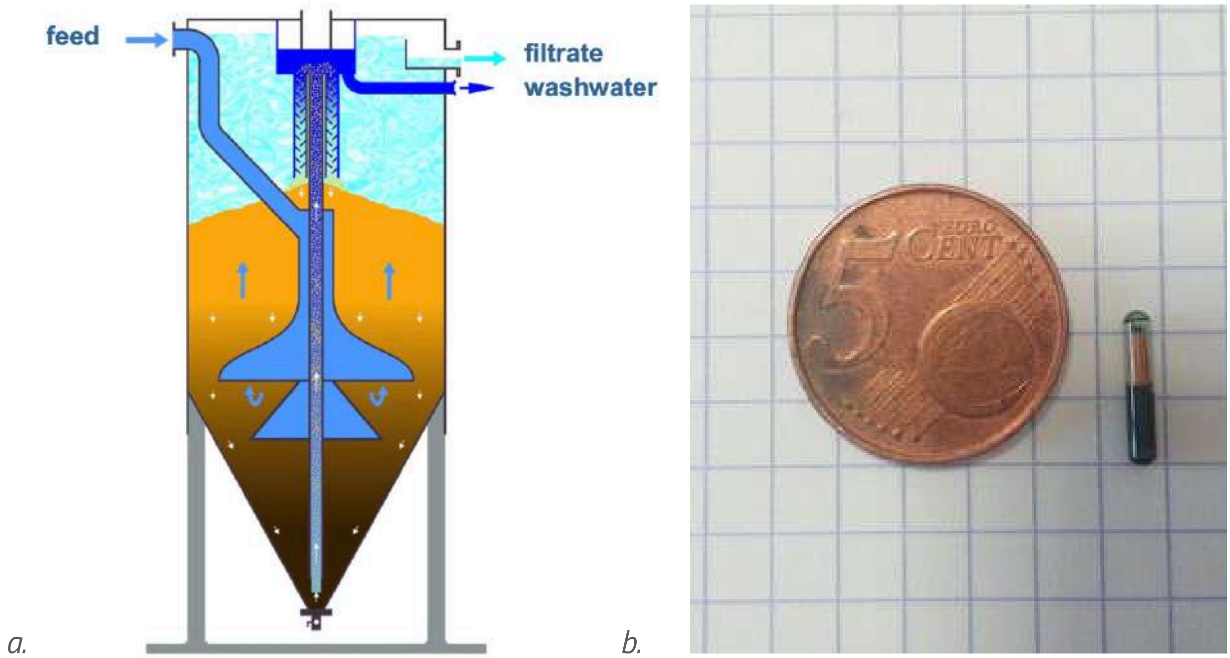

Figure 1 (a) Schematic diagram of moving bed biofiltration (MBFs, ref [9]) and (b) Passive LF RFID tag on 0.5cm graph paper.

The proof-of-concept of *Sand-Cycle* was carried out at pilot-scale at the wastewater works of Franeker [7]. The health of the (bio)filters was visualized on a digital dashboard after translating the tags activity into performance grading factors such as sand circulation rate, active bed volume and filter homogeneity. Later, the smart monitoring tool has been extended to full scale application at various wastewater treatment facilities across EU. The ultimate goal is to increase reliability, reduce plant failures and improve overall treatment performance using this RFID-based technology. In the present article, a practical overview of long-term and full-scale implementation to track MBF's performance at two wastewater treatment plants (case-sites) is provided. System benchmarking was based on sand circulation rate, standard deviation, active bed volume and filter homogeneity. A concise discussion of the historical performance and observed fluctuations related to various aspects of filter operation is included. Furthermore, economic analysis was performed to illustrate the significance of smart and cost-effective monitoring in day-to-day unit operations of wastewater treatment works.

2. Background

Two wastewater treatment works within EU region have been considered as case sites for this study viz. municipal wastewater treatment plant of Franeker (WwTW Franeker, site 1), the Netherlands and Anonymous sewage treatment works (site 2) in the United Kingdom. These two sites handle daily wastewater loads of 14,400 and 8,208 m^3/day (max.) respectively. WwTW Franeker (site 1) is operated by Wetterskip Fryslan (a Dutch water authority) and is situated in the Frisian province of the Netherlands. The treatment cascade of site 1 includes pre-settling, mineral percolating filters and post settling, extended in 2008 with an MBF plant for simultaneous N-P removal in 2008. The MBF plant consists of 6 concrete filter units, each equipped with 4 filter cells. Each filter unit is 5 x 5 m with a bed height of 4 m. The filter cells in each filter unit are not separated and hence each filter unit acts as an individual filter. The MBF plant treats all flow at dry weather flow conditions, a bypass is introduced at rainy weather conditions. The permissible limits of overall effluent (including bypass) are set at values of total-N (10 mg/l, annual average) and total-P (2 mg/l, rolling average in 10 consecutive daily samples). Ferric salt (FeClSO4) and carbon-source (bio-ethanol) are dosed in the filter feed for effective phosphorus removal and biological denitrification. The dosages level of these chemicals is proportional to the actual MBF feed flow, feed NOx-N concentration and feed oxygen concentration (for bio-ethanol) and feed $PO_4{}^{3}$-P values (for $FeClSO_4$).

Figure 2 – Birdseye view of WwTW Franeker (site 1) with the MBF plant on the right

Site 2 is located in Wiltshire County, UK. The site employs primary settling, percolating filters and humus tanks with tertiary moving bed aerated biofilters for ammonia and P removal. MBFs were introduced into the treatment configuration in 2012 with a plant layout based upon 8 similar filter units of each 7 m2 filter area and 2m bed height. The consent levels for effluent discharge are set at 2.4 mg/l ammonium-N (95%ile) and 0.8 mg/l total-P (95%ile). Relevant operational characteristics of the MBFs and Sand-Cycle setup are summarized in Table 1.

Parameter	Site 1	Site 2	Unit
Average Flowrate	14,400	8,208	m^3/day
Population equivalents	60,000	40,000	P.E
Type of MBF	AS500-40-C	DS7000 DYNAOXY	
Year of construction	2008	2012	
No. of filters	24	8	
Average sand circulation rate	4	6	mm/min
Filter bed height	4	2	m
Surface area per filter	6.25	7	m^2
Bed volume per filter	25	14	m^3
Year of *Sand-Cycle* integration	2016	2017	
No. of transponders per filter	100	50	

Table 1 : Overview of the characteristics of moving bed biofilters and Sand-Cycle setup at Sewage Treatment Works site 1 and site 2.

3. Methodology

3.1 Sand-Cycle tool

The RFID tagging system forms the core of the *Sand-Cycle* setup and includes the tags (transponders), a reading device (the reader) and a host system application for data collection, logging, processing and transmission. ID-1001H tags supplied by Trovan Ltd and DorsetID were used as identifiers in the tagging system. The tags are generally attached to the object that needs to be identified but in this case they mimic sand grains and are mixed up (50-100 tags per filter) together in the filter bed. They help in accounting of combined tag-sand grain circulation to monitor the filter operation. The tags operate at a frequency of 128 kHz [8]. Each tag (transponder) has a unique code at the time of manufacture which cannot be duplicated or tampered with. This code facilitates unique and positive identification as the transponder pass through the reader. Each transponder is detected while passing through the reader, which is integrated in the airlift structure of an MBF. The reader inductively energizes and excites the transponder by means of a polarized low frequency electromagnetic field emitted through an antenna. It then receives and processes the code signal bounced back by the transponder. Transponder signal can be read irrespective of their orientation with respect to the reader, also underwater (or in other fluids) and can be used in all weather conditions.

The codes, dates and time stamp of the passing transponders are then transmitted to a decoder that collects data from multiple readers. The decoder is connected to a data logger, which stores data received from the decoder in readable formats. The data logger is equipped with a GPRS modem to transmit the data to the back end of online data server. The data server is converting the raw field data into relevant output data using dedicated algorithms and big data analysis. Output is available 24/7 for the operators via the server's front office and is illustrated as digital dashboards.

3.2 Data and filter performance analysis

Large amounts of data points are generated by the transponders which are translated into in-situ (near real time) filter performance grading factors using fast data analytics. The dashboards present measurements, sand circulation (mm/min), active bed volume, last activity, 4-hour moving average sand circulation speed (mm/min) with standard deviation for defined time period, filter homogeneity and turnover per filter (case-specific). The total transponder count since the start-up is recorded and the in-situ 4-hour average sand circulation rate is displayed. The sand circulation is calculated by converting turnaround time of an individual transponder into speed and averaging it over 4-hour time period. This value depends on the characteristics of the filter used in operation. The time plot of sand circulation is represented as a profile of 4-hour moving average circulation speed indicating the overview of in-situ circulation rates. The spread of upper and lower asymmetrical standard deviation across the average over a defined period of time indicates the filter homogeneity level. A wider spread depicts uneven distributed sand movement over the cross section of filter bed and lower performance level. Other grading factors such as active bed volume and turnover rate per filter are estimated based on the transponder detection over a fixed time period. They help in recognizing degree of filter bed stagnation, clogging, flush out of sand grains and migration of sand across filters. The combination of filter bed resistance and inflow rate with average sand circulation is functional as a controlling parameter for process optimization.

3.3 Economic analysis

Economic quantification of the consequences of filter plant malfunctioning was performed based on the results of surveys on MBF plants performed over the last two decades. Four important parameters like operator attendance, sand loss, energy needs and downtime have been shortlisted for economic analysis. The impact of in-situ and long-term monitoring using *Sand-Cycle* on these individual parameters was carried out to estimate the annual savings per parameter as a function of plant capacity (l/s). Also, 25-year lifetime net savings (in €) have been calculated after deducting the capital costs, maintenance and service charges for the hardware.

4. Results and discussion

4.1 Filter plant performance and off-set conditions

To date, the readers of each filter across the two sites have transmitted about 10,000-22,000 representative signals to the decoder. A huge number of measurement points promotes proper statistical analysis via data analytics and fast data management for better understanding of the sand filtration. The results visualized on a dashboard web-interface provided in-situ status of the filter to the operator.

Figure 3a represents the complete dashboard as seen by the plant operator of WwTW Franeker (site 1) to visualize the near real-time condition of a filter cell. The dashboard elements provided an overall impression of the filter status throughout the period of usage. Of these elements, the circulation rate and profile of circulation rates, upper and lower standard deviation represent the two key indicators to assess the filter health. The circulation rate also acts as the controlling parameter for optimizing removal efficiencies and biological conversions and can be fine-tuned to improve the filter performance. For site 1, the filter activity shows a good performance. However in a concrete layout with multiple filter cells the sand was observed to migrate within the cells of an individual filter unit during operation. This migration was visualized as percentage turnover for each cell (Figure 3b). Fine tuning of air flow per filter cell could promote homogeneous circulation and uniform distribution.

a. b.

Figure 3 (a) The dashboard illustrating the number of RFID tag responses, sand circulation (mm/min), active bed volume, last activity, 4-hour moving average sand circulation speed (mm/min) with standard deviation for last 48 h time period and filter homogeneity (b) the turnover per filter cell displayed at WwTW Franeker

The four-month profile of circulation rates, upper and lower standard deviation of four filter units at site 2 indicated their sand bed movement over the cross-section of individual filter bed and corresponding homogeneity (Figure 4). Uniform distribution of upper and lower speed levels and low levels of deviation implies better homogeneity which leads to better process performance. Higher deviations might correspond to filter anomalies such as stagnant zones. MBF - 1 and MBF - 5 had steady and uniform spread of speeds wheras MBF - 2 and MBF - 7 displayed a more non-uniform spread which corresponds to homogeneity values <75-80%. Non-homogenous sand circulation could be caused by various practical reasons.

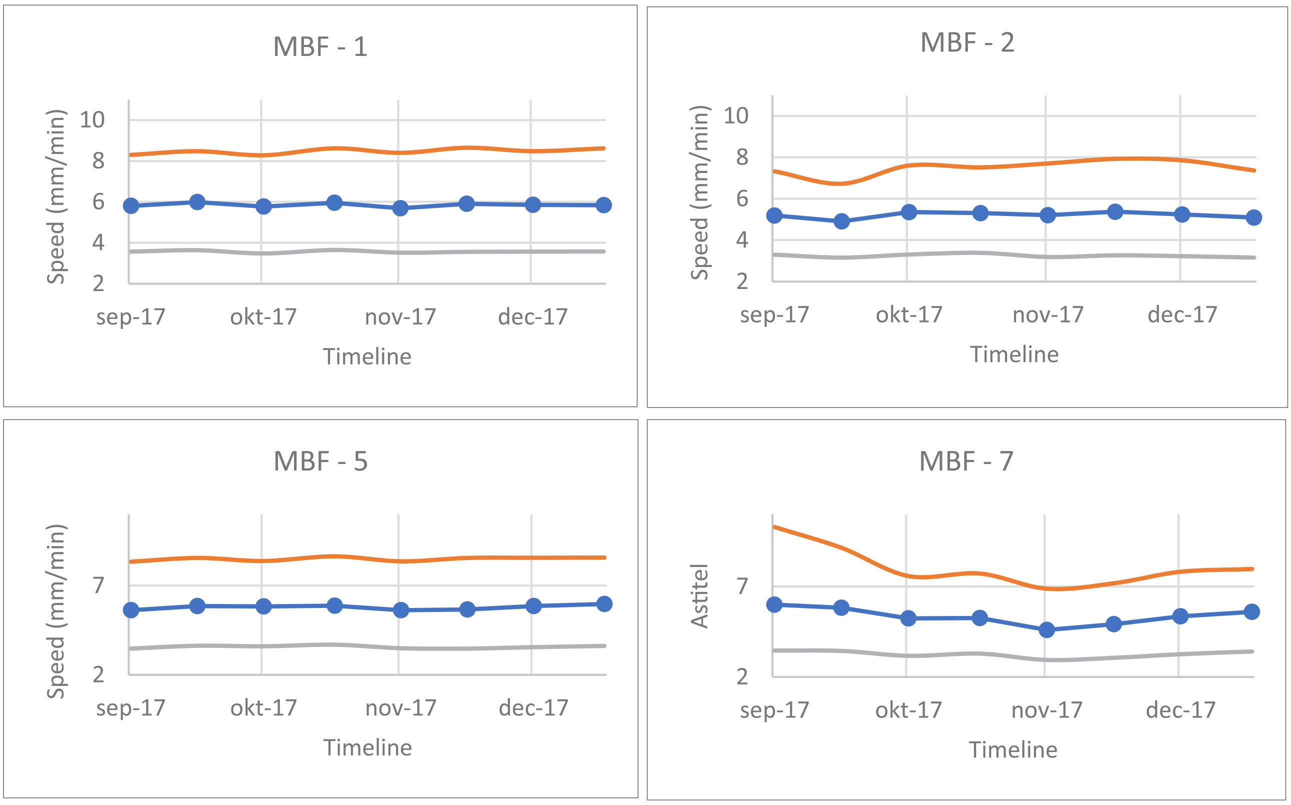

Figure 4. Profile of 4-hour moving average speed and standard deviation (in mm/min) of four filters at site 2 for September 2017 – January 2018. Orange: upper standard deviation, blue with dots: average speed and grey: lower standard deviation.

4.2 Economic analysis

Fast data analytics used in the case studies improved the equipment reliability and reduced energy, maintenance and refurbishment costs. Identification of off-set conditions such as sand loss, downstream pipe blockages and filter bed stagnations via real-time status updates prevent deterioration of filter performance. Digital dashboards provide day-to-day monitoring of the filters and lessen the inspection time and operator attendance. The wireless transmission of operation warnings and diagnostics proved to be advantageous to operate the filter plant at best possible conditions thereby assuring better effluent quality. For example, long-term observation of sand circulation could indicate the status of the airlift setup (wear and tear or energy requirements) and allows timely replacement. Figure 5 estimates the yearly and net 25-year savings made on operator attendance, sand grain loss, energy consumption and downtime in relation to the plant capacity. Manpower costs can be immensely decreased for bigger plants which correspond to increasing trend of 25-year net savings. The considerable cost reduction with respect to the assessed parameters estimates a returns of investment of typically 1-2 years.

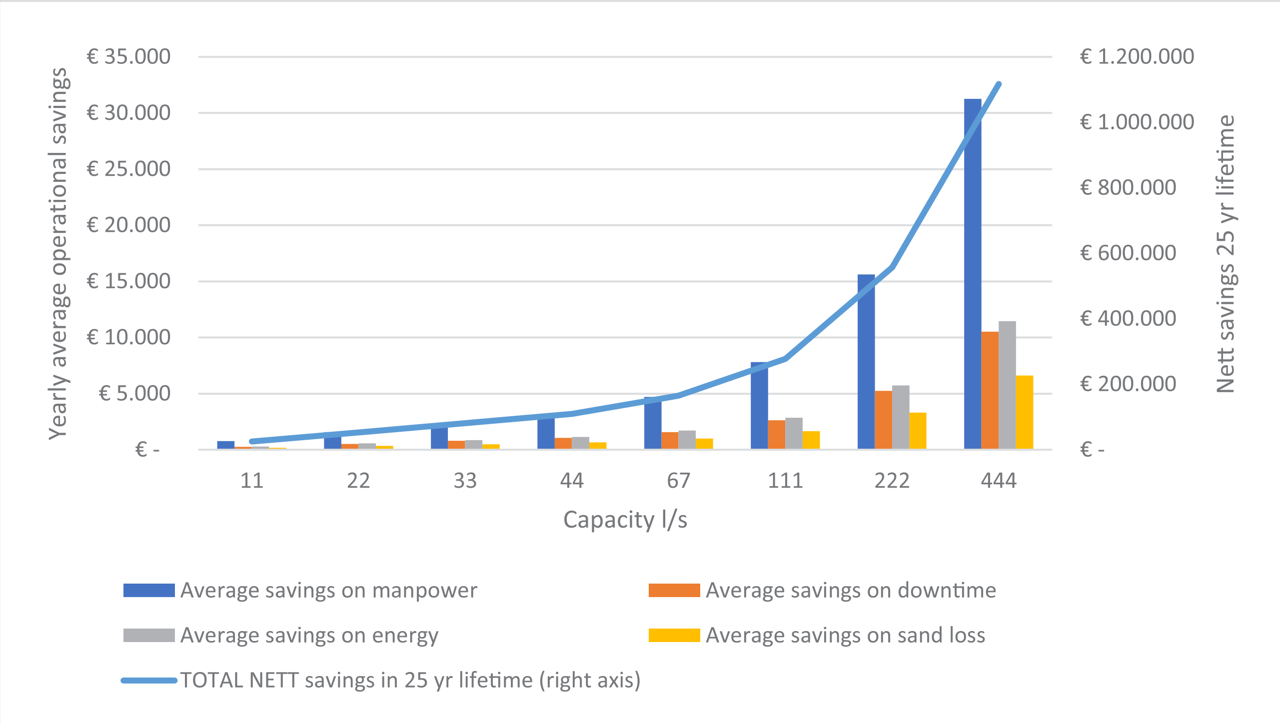

Figure 5 Estimated savings per parameter for 8 plant sizes based on their capacity (l/s).

5. Conclusions

Full-scale applications of a remote real-time tool for monitoring MBF plants has been successfully implemented at wastewater treatment works. Important results of the case studies reveal that:

- RFID technology is a powerful tool for real time monitoring of MBF operations, allowing less maintenance and reaching higher overall plant performance. The results obtained at WwTW Franeker showed excellent reproducibility and added value to the plant operators.
- MBF plants equipped with Sand-Cycle are likely to have increased asset reliability and improved uptime percentages as early detection of dysfunctions and process disturbances allow the operators to reduce plant attendance without losing control.
- The return on investment of the tool, typically less than 2 years, allows the asset manager to justify the implementation of the technology.
- Introduction of similar advanced RFID monitoring technologies could pave path for effective and efficient wastewater management.

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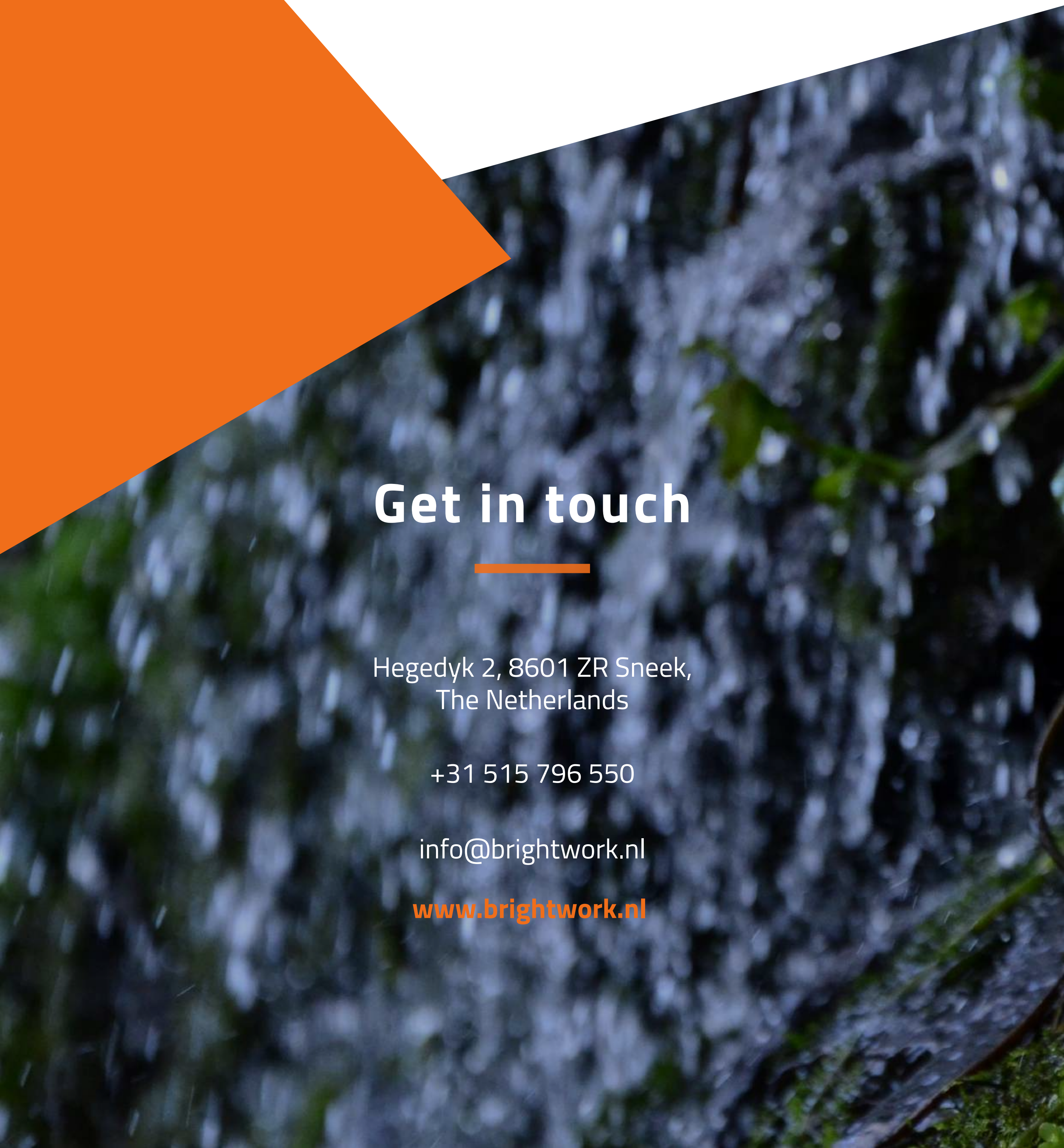

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