Deliverable 4.3.4

On-line monitoring of CSO: sewer and receiving waters

SEVENTH FRAMEWORK PROGRAMME

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Author(s)
Marta Rodrigues, Luís David, Anabela Oliveira, André B. Fortunato, José Menaia, Joana Costa, Tiago Mota, João Rogeiro, Gonçalo Jesus, Paulo Morais, João Palma, Rafaela Matos

LNEC – Laboratório Nacional de Engenharia Civil, Portugal

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Contents

1 OVERVIEW

Monitoring combined sewer overflows (CSO) is both a legal requirement and a challenge for the management of urban drainage systems and the protection of their receiving water bodies. Since extreme rainfall events are expected to become more frequent and severe due to climate change, increasing the frequency, the volumes and even the pollution loads discharged by CSO into the receiving water bodies, this monitoring is becoming increasingly important.

Challenges are associated with the development of integrated monitoring networks, allowing the understanding of the propagation and impacts of the overflows from the sewer to the receiving waters. The nature of CSO, highly variable in occurrence and duration, adds to this challenge, which can be overcome by continuous monitoring. Until recent years, the characterization of most of the water physical-chemical parameters required the collection of a significant number of discrete or composite samples and their laboratory analysis, which put severe limitations on the comprehension of the water quality evolution during and between storm events. The recent availability of commercial spectrophotometric probes that allow the continuous measurement of parameters such as turbidity, total suspended solids (TSS), chemical and biological oxygen demand (COD and BOD), among others, is revolutionizing the monitoring systems. However, the installation of on-line monitoring networks in sewer and receiving water bodies is also challenging. Flow characteristics (e.g. highly turbulent, and in some cases bidirectional due to tides) and the suspended and floating material may limit the robustness of the network, the integrity of the sensors and the quality of the data. Finally, other important water quality parameters required for model forecasts and early-warning of faecal contamination events in the receiving water bodies (e.g. faecal bacteria) still cannot be measured by existing sensors. Hence, these parameters have to be estimated by indirect methods.

The research described herein contributes to overcome some of these challenges. A combined network for the on-line monitoring from the sewer to the receiving waters was designed, implemented and tested. This network, composed by both conventional (e.g. thermometer) and sophisticated sensors (spectrophotometric, ammonium and nitrates probes), aims to provide continuous data, feeding and supporting a platform for forecast and early-warning of faecal contamination events (Oliveira *et al.*, 2014). It also provides long-term data on the system, essential for a further understanding of its dynamics and response to extreme events, and, ultimately, the development of management plans. To guarantee the quality of the data, procedures were developed for the calibration of the sensors based on local data, and for the identification of outliers through the processing and analysis of raw data. On-going research is also seeking for relationships between parameters measured by spectrophotometric and ammonium probes (e.g. COD, TSS, nitrates, ammonia, turbidity, fingerprint spectra) and faecal bacteria concentration, to support forecasts of the faecal contamination plume in the receiving waters and the early-warning procedure.

This pilot monitoring network is under demonstration in the Lisbon PREPARED site (as described in David *et al.*, 2014).

2 ON-LINE MONITORING NETWORK CONCEPTION, IMPLEMENTATION AND OPERATION

2.1 Synoptic field surveys: from the sewer to the receiving waters

Field surveys were set as a preliminary step for the design of the monitoring network. This step was crucial as it provided a better knowledge of the system to be monitored and, consequently, it supported the specification of the sensors to acquire, the selection of the location of the on-line sampling stations and the design of the network and its infrastructures.

To define these field surveys, a synoptic approach was used to provide an integrated overview of the system to be monitored, which includes the drainage system and the receiving waters (David *et al*., 2013). Surveys were undertaken in the water front of the city of Lisbon covering the wastewater treatment plant (WWTP), the Alcântara outfall and the Tagus estuary (Figure 1; David *et al*., 2014). A total of 5 surveys were carried out in all sections of Figure 1, for 13 hours (a complete tidal cycle) and for dry- and wet-weather conditions. Temperature, pH, conductivity, salinity, dissolved oxygen and ammonia were measured hourly by probes. Water samples were collected every four hours for laboratory analysis of the following parameters: pH, turbidity, conductivity, total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), ammonium, nitrites plus nitrates, phosphates, faecal coliforms and *Escherichia coli* (*E. coli*). Additional samples were collected just in the sewer and estuary on-line monitoring stations, especially for wet-weather.

Figure 1 - Location of the sampling stations (blue circles for the sewer stations; yellow circles for the estuary stations). The on-line monitoring sensors were installed at stations 5 and 3 in the sewer and in the receiving waters, respectively.

These surveys also allowed the calibration and validation of a coupled hydrodynamics / faecal contamination model – ECO-SELFE – of the receiving waters (Rodrigues *et al*., 2011, 2013; David *et al*., 2014).

At a later stage, synoptic field surveys also provided data to calibrate the sensors acquired for the on-line monitoring network (see 2.2 and 2.3).

2.2 Design, installation, operation and maintenance of the on-line monitoring network

The location of the on-line monitoring equipment was selected in order to provide an integrated overview of the system behaviour, i.e. both in the sewer system and the receiving waters, during CSO, and to be representative of the concentrations at these sites. Other criteria for site selection included: access to essential infrastructures (e.g. electricity, internet), ability to obtain permission to install the equipment and protection from vandalism (Caradot, 2012). Based on these criteria two sites were selected: one in the sewer system, located in the diversion sewer from the CSO to the wastewater treatment plant (Alcântara WWTP) and the other in the receiving waters (Tagus estuary), located in front of the sewer outfall (Figure 1; David *et al.*, 2014).

The on-line monitoring equipment selected for each of the stations was (Figure 2):

- Sewer station
  1. UV-Vis spectrophotometric probe (2 mm optical window), spectro::lyser S::CAN, with municipal WWTP influent and sewer calibration (TSS, COD, soluble COD and nitrates);
- Receiving waters station
  1. UV-Vis spectrophotometric probe (5 mm optical window), spectro::lyser S::CAN, with municipal WWTP effluent calibration (TSS, COD, soluble COD and nitrates);
  2. ammonium and nitrates probe, ammo::lyser S::CAN (ammonium, nitrates, pH, temperature);
  3. conductivity and temperature probe, condu::lyser S::CAN (conductivity, temperature, salinity);
  4. dissolved oxygen probe, oxi::lyser S::CAN (dissolved oxygen, temperature).

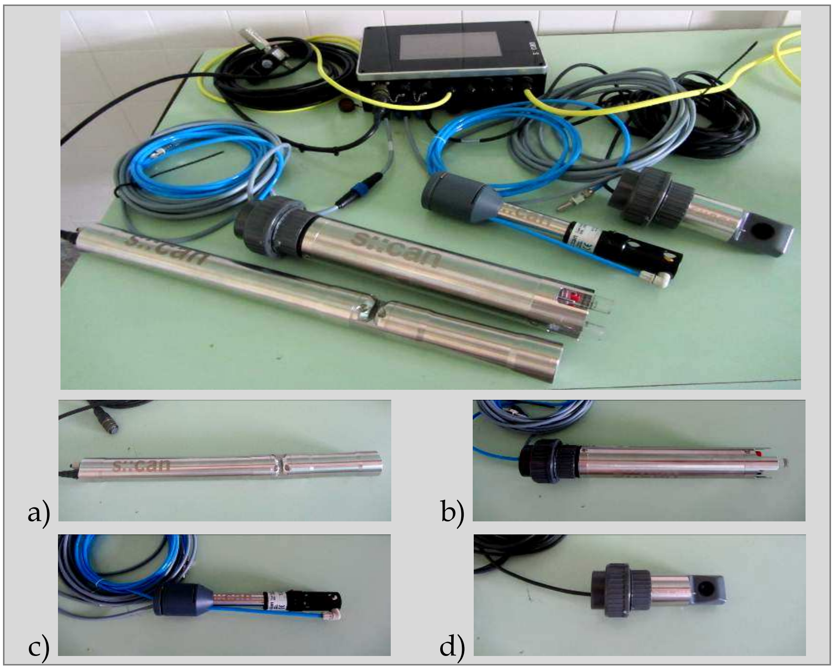
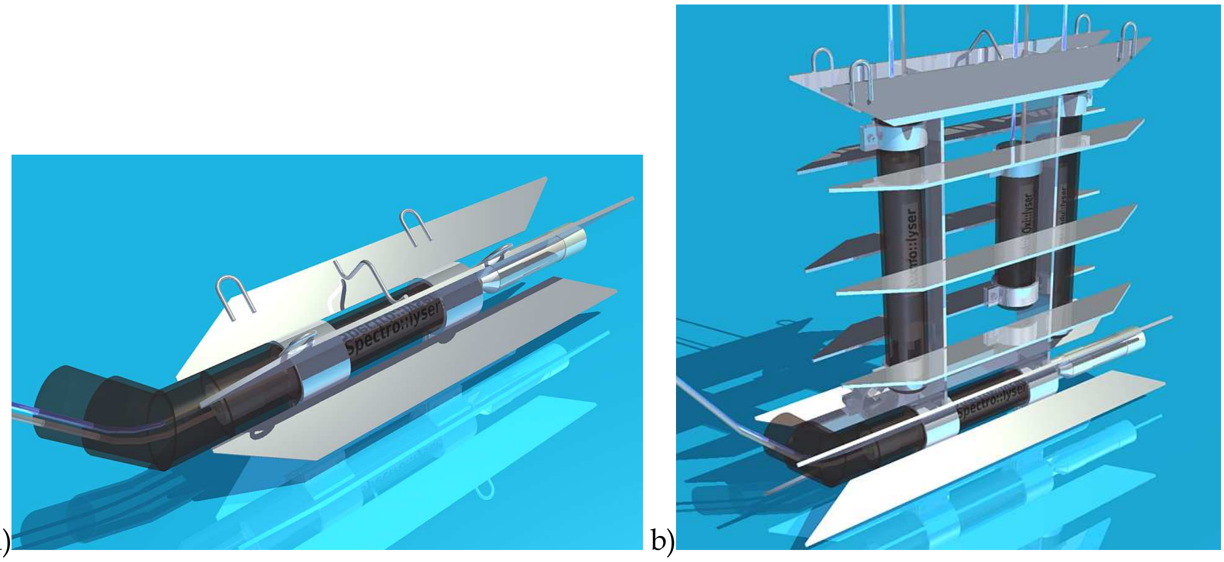


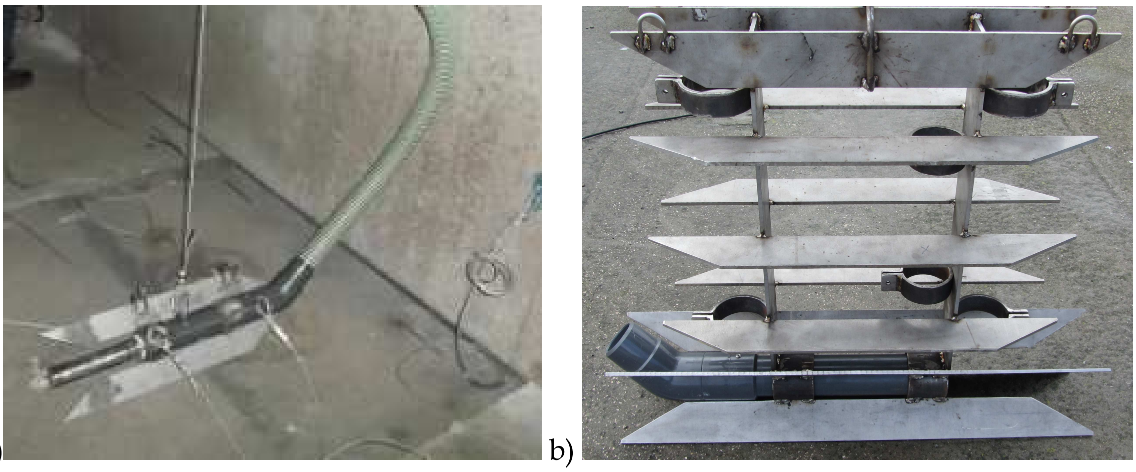
Figure 2 - Sensors installed at on-line monitoring station and Con::cube S::CAN controller: a) spectro::lyser S::CAN (UV-Vis spectrophotometric probe calibrated for COD, TSS and nitrates), b) ammo::lyser S::CAN (ammonium, nitrates, pH, temperature), c) condu::lyser S::CAN (conductivity, temperature, salinity) and d) oxi::lyser S::CAN (dissolved oxygen, temperature).

At both locations the monitoring sensors are controlled on-line using the Con::cube S::CAN controller, which communicates with the real-time platform (Figure 2; Oliveira *et al.*, 2014).
The design of the on-line monitoring network for CSO took into account the specificities of the selected sites. Innovative supporting structures were designed and built to support and protect the sensors in the harsh measurement environments (Figure 3, Figure 4). The design of these structures also uses the flow lines and the turbulence in the sewer, and the bidirectional flows due to tides in the estuary to maintain their stability and improve self-cleaning. These structures were built in stainless steel to resist corrosion.



a) b)

Figure 3 – Conceptual design of the support structures of the sensors, specifically designed to address the flow characteristics in the a) sewer and b) receiving water body.



a) b)

Figure 4 – Support structures of the sensors: a) sewer and b) receiving water body.

At the estuarine monitoring station, an environmental shelter was also installed to protect the controller and the cleaning equipment, and also to provide the electrical supply (Figure 5). To guarantee the safety of the technicians and of the sensors, due to the weight of the sensors' supporting structure, the apparatus is raised and lowered with an electrical hoist. All the materials used in these infrastructures were selected to guarantee their resistance to corrosion by

salt water. The environmental shelter is ventilated to prevent overheating during the summer season. The equipment of the estuarine monitoring station is powered from an existing 3-phase electric supply for hoists (400V, 50Hz), without neutral point, using a 400/230V, 2.5kVA single-phase transformer. Steel reinforced cables had to be used up to the supply point due to exposure to mechanical actions. The electromagnetic immunity of the instrumentation and data acquisition systems relatively to disturbances in the supply, which was a major concern, was achieved by using the transformer for isolation, earthing a secondary neutral point and a signal ground conductor to the hoist rail structure and using a 600VA uninterruptible power supply (UPS) to supply the sensitive equipment separately from the air compressor and general use circuits.
Overviews of the installed monitoring stations are presented in Figures 5 and 6.

a)
b)
c)

Figure 5 - Receiving waters (Tagus estuary) on-line monitoring station: a) environmental shelter and supporting structures, b) detail of the supporting structure of the sensors and hoist, and c) Con::cube S::CAN controller and air compressor installed inside the environmental shelter.

Figure 6 - Sewer on-line monitoring station: sensor installation and maintenance.

Data are measured continuously at the monitoring stations, with 5 minutes intervals. Measured data are transmitted hourly using GSM/GPRS and stored in SQL databases. Data can be accessed on-line through a platform for forecast and early-warning of faecal contamination events (Figure 7; Oliveira *et al.*, 2014).

Maintenance procedures were established and implemented to guarantee the safety of the sensors and the quality of the data. Three levels of maintenance procedures are considered:

- <u>Automated cleaning</u> – automated cleaning is promoted using air compressors, to clean the probes every 5 minutes in the sewer station and every 30 minutes in the receiving waters station (Figure 5c);
- <u>Periodic cleaning and inspection</u> – procedures of manual cleaning of the equipment, probes and UV-Vis measurement window and visual inspections of the infrastructures (e.g. status of the cables, corroded parts) are performed on a weekly basis, at both the sewer (Figure 6) and the receiving waters stations. For safety reasons at least 3 technicians are required for this activity in the sewer and 2 technicians are required in the

receiving waters. Checklists were developed for this purpose, to guarantee that all the relevant components of the monitoring installation are verified and that a registry of inspections and failures is maintained (Figure 8);

- Out-of-schedule cleaning – supplementary procedures for cleaning the sensors may be undertaken when needed (e.g. after severe rain events trash/rubbish may accumulate in the supporting structures and needs to be removed – Figure 9).

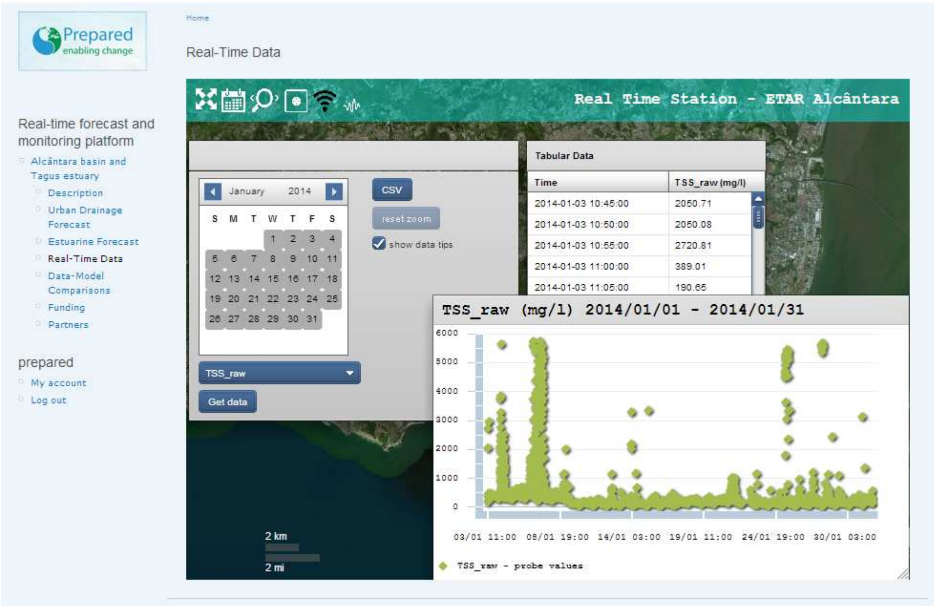


Figure 7 – PREPARED platform: on-line data of TSS from the sewer monitoring station.

Sistema de Monitorização em Tempo Real

Folha de Registo de Manutenção Periódica

Local: Cais de Alcântara

Data	Estruturas Exteriores - Verificação			Sondas - Limpeza					Abrigo - Verificação			Observações	Responsável
	Cabos	Estruturas de Suporte	Outro Material	Remoção de Detritos	Célula Óptica Spectro	Ammo	Condu	Oxi	Estado Geral	Compressor	Cabos Interiores		

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Figure 8 – Example of the checklist used in the periodic cleaning and inspection of the receiving waters on-line monitoring station (in Portuguese).

Figure 9 – Trash removed from the receiving waters on-line monitoring station during an out-of-schedule cleaning after an extreme rain event (November 30, 2013).

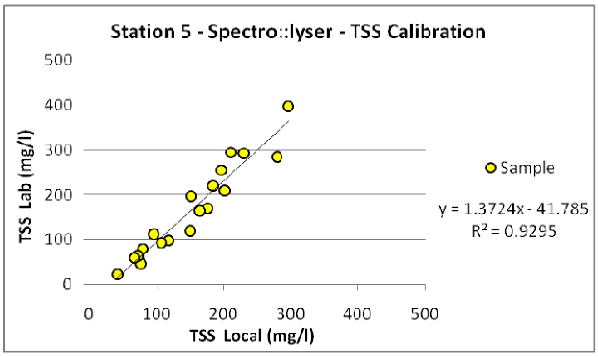
2.3 Calibration, verification, data processing and analysis

Data collected during the synoptic field surveys were used to calibrate the UV-Vis spectrophotometric probes and verify the quality of the data measured.

Laboratory results from grab samples confirmed the accuracy of TSS and COD measurements from the UV-Vis spectrophotometric probe installed in the sewer. Calibration of the measurements with 19 samples collected in dry- and wet-weather conditions provided coefficients of determination of 0.93 and 0.86, for TSS (Figure 10) and for COD, respectively.

The accuracy of the calibration of the UV-Vis spectrophotometric probe installed in the receiving waters is lower than the one observed for the sewer probe. Calibration of the measurements with 19 samples collected in dry- and wet-weather conditions provided correlation coefficients of 0.70 for TSS (Figure 10) and 0.37 for nitrates. The slopes of the linear regression are also far from 1. These results show that the default calibration of the sensor (municipal WWTP effluent calibration) is inappropriate for this site and that local calibration is required. The optical window may also need to be enlarged to 25 mm. The highest concentration of TSS measured in the estuary during calibration surveys (Figure 10) was sampled during an important CSO event. COD was not calibrated, since the determination of COD in the laboratory was not possible for salt water.

Data measured and transmitted on-line to the webGIS platform must be checked and processed aiming to detect errors and inconsistencies and to purge the series from outliers and spurious data (Fletcher and Deletic, 2008; Lepot *et al*., 2013). In a first phase, this work must use data from a representative period of time, in order to find criteria for an automated processing to be used in continuous / automatic mode later. The S::CAN software from the spectrophotometric probe provides not only the instantaneous measurements of the calibrated parameters (the "raw" values of TSS, COD, soluble COD and nitrates) but also smooth series for the parameters (called "clean" series), obtained by a moving average. However, if the probe is measuring erroneous values, those data are being included in the "clean" series. It was found that several anomalously high values were registered, which should be removed from the series. In the sewer system, most outliers occur during the low flow night periods. Therefore, two levels of filters were created for each measured parameter: one to identify and remove outliers and another to detect dubious values. As some disturbances may result from rainfall or a flush due to an increase of the hydrograph, another routine identifies if the dubious values occur during rainfall periods or are associated with changes in the flow hydrographs. The decision to remove these dubious values from the series has to be done manually. Missing or removed data are filled by interpolation for short dry-weather periods, but are left empty for rainy or long wet-weather periods, in order to show the lack of correct data for important periods.

a) 

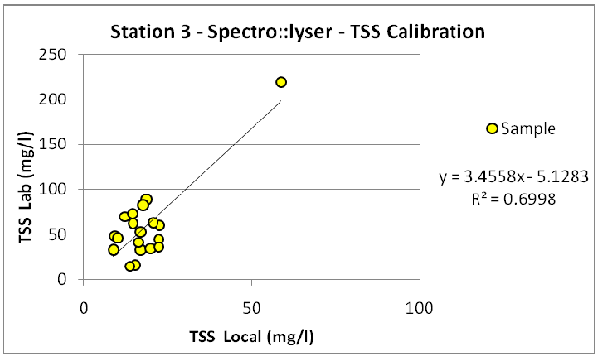
b) 

Figure 10 - Example of the calibration of the UV-Vis spectrophotometric probes. TSS measured by the UV-Vis spectrophotometric probe vs. TSS measured in the laboratory: a) sewer system and b) receiving waters.

2.4 On-line monitoring in support of model forecasts and early-warning

Besides providing data for the continous surveillance of the sewer system and adjacent receiving waters, on-line monitoring is also fundamental to support the model forecasts and to verify the quality of these predictions (Oliveira *et al.*, 2014; David *et al.*, 2014). Moreover, on-line monitoring of the CSO and their water quality, combined with model forecasts, will also be used to setup early-warning parameters and conditions.

To support the faecal contamination forecasts and early-warning, on-going research is seeking for relationships between parameters measured by the installed sensors (UV-Vis spectrophotometric and ammonium probes) and faecal bacteria concentration. In the sewer promising relations were found between faecal bacteria concentrations and TSS and COD, with correlation coefficients of about 0.6. Preliminary analyses also showed promising results for the estimation of faecal bacteria concentrations based on the ammonium concentrations in the receiving waters. However, as ammonium and nitrate probes are not suited for seawater environments (as is the water front of the Alcântara basin in the Tagus estuary) on-going research is also seeking corrections of the probe's measurements, based on the positive correlations found between salinity and ammonium and nitrates in the receiving waters.

3 CONCLUSIONS AND RECOMMENDATIONS

An integrated network for the on-line monitoring of CSO was designed and installed with success in the Lisbon PREPARED demonstration area. This network encompasses two continuous monitoring stations: one installed in the sewer system and another installed in the receiving waters. Conventional (e.g. thermometer) and sophisticated sensors (UV-Vis spectrophotometric, ammonium and nitrates probes) provide on-line water quality data to feed an integrated webGIS platform to support the surveillance and early-warning of faecal contamination events.

Major issues regarding the design of the network were the site selection and the development of stainless steel innovative structures specifically designed for turbulent and bi-directional flows. The selection of adequate materials for all infrastructures, in particular the ones exposed to wastewater and sea water, is crucial to guarantee the robustness of the structure and to avoid its deterioration over time. Electromagnetic compatibility of equipment and power supply, as well as automated and regular cleaning and inspection is also a requirement for these networks to assure the quality of the data. The monitoring network has been in operation for over 1 year.

In a context of climate change and of increasing extreme rainfall events, on-line networks combined with model forecasts, as the one developed in the scope of PREPARED, are useful tools to support decision-makers in the development of prevention, mitigation and adaptation strategies to reduce the risks for the public health of faecal contamination events.

Further research is needed regarding the faecal bacteria concentration estimation based on the parameters measured by the available sensors.

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5 ACKNOWLEDGEMENTS

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