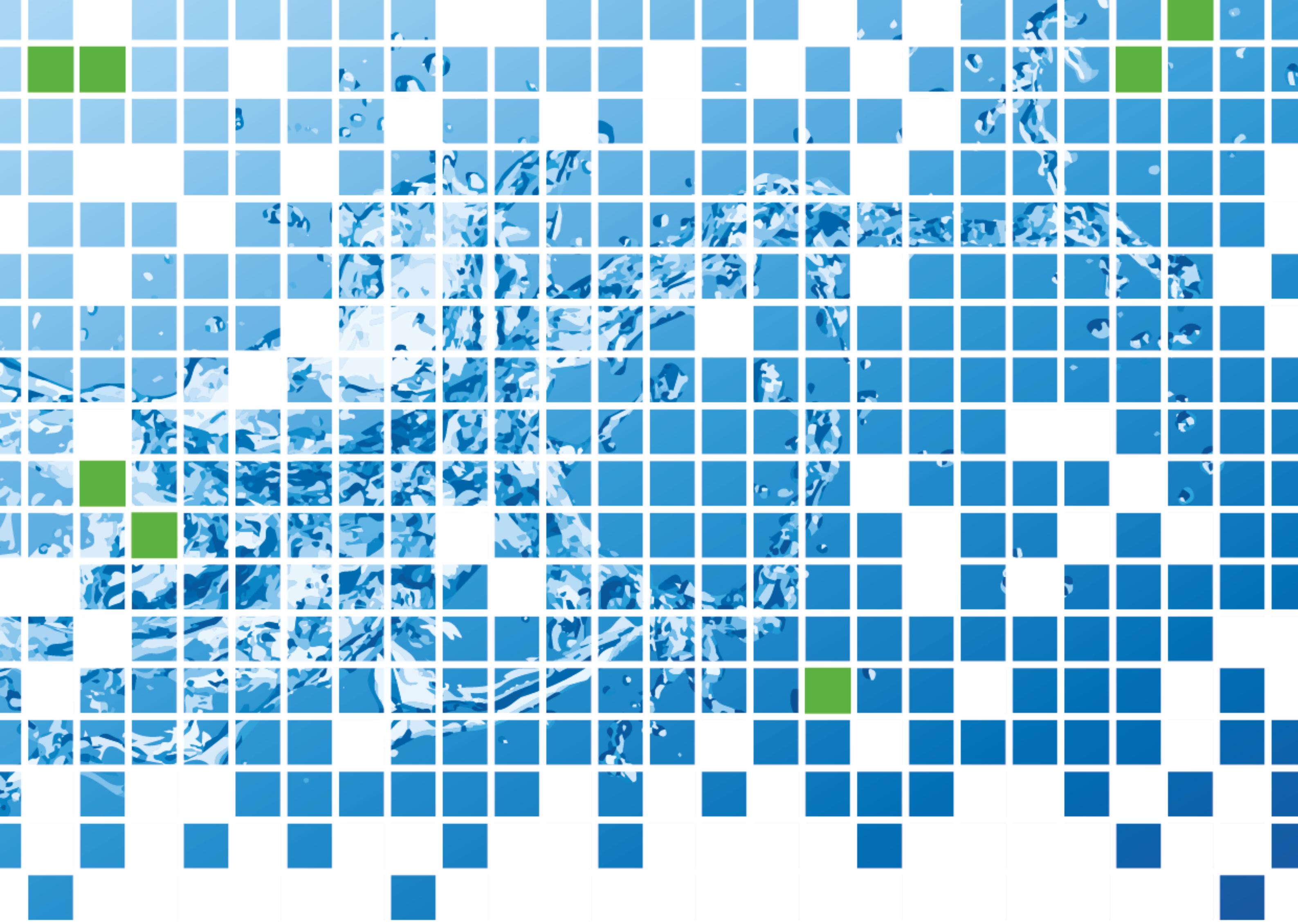

Co-UDlabs

BUILDING COLLABORATIVE URBAN DRAINAGE RESEARCH LABS COMMUNITIES

D6.1. Report on review and selection of new/ emerging monitoring technologies to be tested in T6.1.2.

Date of delivery – 30/04/2022
Author – Jörg Rieckermann (EAWAG)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°101008626

DOCUMENT TRACKS DETAILS

Project acronym	Co-UDlabs
Project title	Building Collaborative Urban Drainage research labs communities
Starting date	01.05.2021
Duration	48 months
Call identifier	H2020-INFRAIA-2020-1
Grant Agreement No	101008626

Deliverable Information	
Deliverable number	6.1
Work package number	6
Deliverable title	Report on review and selection of 8 new and emerging monitoring technologies to be tested in T6.1.2.
Lead beneficiary	EAWAG
Author	Jörg Rieckermann
Due date	30.04.2022
Actual submission date	29.04.2022
Type of deliverable	Report
Dissemination level	Public

Version Management

Revision history and quality check			
Version	Name	Date	Comment
V 0.1	Mathieu Lepot, INSA	01/10/2021	Mathieu Lepot, INSA, initial draft
V 0.2	Pierre Lechevallier, Eawag	15/03/2022	Contribution from partners, detailed list of sensors
V 0.3	Jörg Rieckermann, Eawag	01/04/2022	Internal review, adapted structure
V 0.4	Juan Naves, UDC Mathieu Lepot, INSA	22/04/2022	Internal review, contribution from UDC and INSA
V 0.5	Antonio Moreno Rodelas, Deltares	23/04/2022	Internal review, contribution from Deltares
V 0.6	Jörg Rieckermann, Eawag	27/04/2022	Sent to partners for review

V 0.7	James Shucksmith, USFD	28/04/2022	Internal review, contribution from USFD
V 0.8	Pierre Lechevallier, Eawag Jose Anta, UDC	29/04/2022	Internal reviews
V1.0	Jörg Rieckermann, Eawag	29/04/2022	Final version
V1.1	Mathieu Lepot, INSA Antonio Moreno Rodelas, Deltares	23/05/2022	Additional details on PAH sensor and Pipe mapping tests
V1.2	Juan Naves, UDC Jose Anta, UDC Jörg Rieckermann, Eawag	26/05/2022	Internal reviews

BACKGROUND: ABOUT THE CO-UDLABS PROJECT

Co-UDlabs is an EU-funded project aiming to integrate research and innovation activities in the field of Urban Drainage Systems (UDS) to address pressing public health, flood risks and environmental challenges.

Bringing together 17 unique research facilities, Co-UDlabs offers training and free access to a wide range of high-level scientific instruments, smart monitoring technologies and digital water analysis tools for advancing knowledge and innovation in Urban drainage systems.

Co-UDlabs aims to create a urban drainage large-scale facilities network to provide opportunities for monitoring water quality, UDS performance and smart and open data approaches.

The main objective of the project is to provide a transnational multidisciplinary collaborative research infrastructure that will allow stakeholders, academic researchers, and innovators in the urban drainage water sector to come together, share ideas, co-produce project concepts and then benefit from access to top-class research infrastructures to develop, improve and demonstrate those concepts, thereby building a collaborative European Urban Drainage innovation community.

The initiative will facilitate the uptake of innovation in traditional buried pipe systems and newer green-blue infrastructure, with a focus on increasing the understanding of asset deterioration and improving system resilience.

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LIST OF ABBREVIATIONS

Acronym / Abbreviation	Meaning / Full text
Co-UDlabs	Collaborative Urban Drainage Laboratories
HALL	Eawag experimental hall, Co-UDlabs research infrastructure
JRA	Joint Research Activity
LiDAR	Light Detection and Ranging
PAH	Polycyclic aromatic hydrocarbons
PLS	Partial Least-Squares
RI	Research Infrastructure
SME	Small and Medium Enterprise
TA	Transnational Access
TRL	Technology readiness level
UWO	Urban Water Observators, Co-UDlabs research infrastructure
WWTP	Wastewater treatment plant

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EXECUTIVE SUMMARY

In this deliverable D6.1, we describe the review of innovative sensors technology in the Co-UDlabs project and give details about the 8 selected sensors and the envisioned plan to test their performance. We applied a three-phased approach, where we first generated a comprehensive list of 55 sensors and digital monitoring technologies, which had a strong focus on online water quality monitoring. This list was subsequently narrowed down to a final list of 8 sensors that measure, i) coliforms continuously with in-situ fluorescence, ii) electrical conductivity with low-power, iii) water velocities with cameras, iv) Ammonium and other pollutants with a submersible spectrophotometer, v) multiple pollutants with hyperspectral imaging, vi) Polycyclic Aromatic Hydrocarbons (PAH) with in-situ fluorescence, vii) pipe condition, and viii) 3D sediment beds remotely with LiDAR.

With this selection we achieved a satisfactory balance between monitoring technology with the potential to advance urban drainage research and technology which can directly deliver added value to practitioners. 4 of the 8 instruments have a low technology readiness level (TRL) and have been selected for their potential to advance urban drainage research. In contrast, 3 other sensors have a TRL of 8 or higher, which means that, if tests are successful, they could readily be integrated into new monitoring services.

The final list of selected sensors is of special interest for work package (WP) 6 and WP9, to provide smart monitoring solutions and inform the transnational access activities. It provides the necessary input for Task 6.1.2. to test the sensors in the laboratory and under real-world conditions. It directly contributes to addressing the project goals defined in objectives No. 6.2 and 6.3 of the Grant Agreement, as well as Main Objective 3, and to a lesser degree to objectives No. 2.2 and Main Objective 2.

1. INTRODUCTION

Urbanization and climate change put pressure on both urban drainage systems (UDS) and natural aquatic ecosystems. IT and smart monitoring are cornerstones to design, operate and upgrade assets, and efficiently protect and improve the quality of natural ecosystem. However, reliable information on the performance of UDS and on pollutants emitted from UDS into the environment is very limited at the European scale, and evidence-based management of UDS needs to be boosted.

In the future "open-data" society, many more pseudo-"intelligent" sensors will be installed, with a need for disruptive approaches. This leads to three fundamental issues: First, most installed current sensors in UDS are related to hydraulic measurements (detection of overflows, levels in tanks and pipes, velocity/flows) and do not give the necessary information on pollutants and ecological impacts and asset condition. So, new signals and information are needed. Second, sensor signals are not reliable because of poor data quality. Third, current urban drainage utilities are not well prepared to deal with the digital water revolution[1][2].

Therefore, the JRA1 in the Co-UDlabs project (WP6) aims to support the transition towards a digitized, informed and evidence-based decision process. To support urban drainage research and practice with mature sensor and communication technology for the underground and hazardous environments found in UDS, the main goal of Task 6.1 in the Co-UDlabs project is to review new and emerging sensing technologies and methods, to select the most promising ones, and evaluate their performances under laboratory and field conditions.

In this deliverable (D6.1), we describe the review of innovative sensor technology in the Co-UDlabs project and present the 8 selected sensors and the envisioned plan for their testing (section 4). The instruments are of special interest for WP6 and WP9 to provide smart monitoring solutions and inform the transnational access activities. It delivers the necessary input for Task 6.1.2., the testing of the sensors.

The results from task T6.1.1. contribute to addressing the project goals defined in objectives No. 6.2 and 6.3 in the project proposal. The work done in T6.1.1. has demonstrated that relevant water sensors are available or under development to give the necessary information on health impacts of wet weather discharges, pollutants and asset condition. This will help to provide new products and services that will support evidence-based management, as defined in Main Objective 3 of the project proposal. This will be a Key Component to achieving a Water Smart Society[3] as described the Strategic Innovation and Research Agenda of the Water Europe platform.

In the following, we will first describe the general research needs for UDS science and practice and then describe the process of sensor review and selection, third, present the sensors. Finally, we summarize the expected outcomes for the Co-UDlabs project and outline the next steps.

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[1] Eggimann, S., Mutzner, L., Wani, O., Schneider, M.Y., Spuhler, D., Moy de Vitry, M., Beutler, P., Maurer, M., 2017. The Potential of Knowing More: A Review of Data-Driven Urban Water Management. Environ. Sci. Technol. 51, 2538–2553. https://doi.org/10.1021/acs.est.6b04267

[2] Blumensaat, F., Leitão, J.P., Ort, C., Rieckermann, J., Scheidegger, A., Vanrolleghem, P.A., Villez, K., 2019. How urban storm- and wastewater management prepares for emerging opportunities and threats: digital transformation, ubiquitous sensing, new data sources, and beyond – a horizon scan. Environmental Science and Technology 53, 8488–8498. https://doi.org/10.1021/acs.est.8b06481

[3] https://watereurope.eu/wp-content/uploads/2019/07/Water-Europe-SIRA.pdf

2. ANALYSIS OF RESEARCH NEEDS FOR URBAN DRAINAGE RESEARCH AND PRACTICE

In a recent book on monitoring urban drainage systems[4], the authors distinguish between three different types of metrologies: (i) scientific, fundamental metrology, (ii) applied (technical, industrial) metrology and (iii) commercial or legal metrology. They argue that in urban drainage systems, monitoring needs concern "applied metrology" because even urban drainage researchers do not work on fundamental metrology but use available technology to better understand relevant processes.

In urban drainage practice, the main goal of utilities and commercial service providers is to make sure that the monitoring system performs as planned, which implies to frequently evaluate all involved components, to regularly check data availability and quality, to periodically calibrate sensors and analyze the data periodically to ensure that the obtained information meets the standards as defined in the objectives.

Monitoring needs in research concern sensors (and/or digital technologies) which deliver novel data or facilitate a more detailed Spatio-temporal monitoring. Whereas monitoring technology for water quantities, such as water levels and velocities, is comparably mature[5], researchers are mostly interested in new sensors, e.g. to improve water quality monitoring. This concerns more specialized substances, such as micropollutants, or pathogens[2] or more spatially resolved monitoring of rainfall-runoff processes[6]. In addition, their instruments and monitoring platforms, such as data loggers, should be open and customizable, e.g., to adapt the internal processing of the raw sensor signals, to develop a custom data analysis, for detailed assessment of the raw data, etc. Also, low technological readiness levels (TRL) (Figure 1) are acceptable.

Two examples of state-of-the-art research sensors are, the UBflow (Ubertone, France) for measuring turbulence and turbidity ratios with ultrasound technology, or (hyper)spectral imaging techniques for non-contact pollution monitoring[7] (Section 4.6.).

In contrast, practice is more concerned to better understand the functioning of a utility's infrastructure, which translates into reliable sensors that support effective decision-making[3]. Here, monitoring solutions must be cost-effective[8] and fit-for-purpose. Operational issues, such as compliance with work safety and ATEX regulations, are very important because of liability issues. In addition, a "good" sensor is often characterized by reliable business relationships and customer service which solves issues when they arise. Examples of practice sensors would be sensors that have internal quality checks[9], or those which are easy to maintain and thus require fewer resources.

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[4] Betrand-Krajewski, J.-L., 2021. Metrology in Urban Drainage and Stormwater Management: Plug and Pray. IWA publishing. https://doi.org/10.2166/9781789060119

[5] Larrarte, F., Lepot, M., Clemens-Meyer, F.H.L.R., Bertrand-Krajewski, J.-L., Ivetić, D., Prodanović, D., Stegeman, B., 2021. Water level and discharge measurements. https://doi.org/10.2166/9781789060119_0035

[6] Fencl, M., Rieckermann, J., Sýkora, P., Stránský, D., Bareš, V., 2015. Commercial microwave links instead of rain gauges: fiction or reality? Water Sci. Technol. 71, 31–37. https://doi.org/10.2166/wst.2014.466

[7] Agustsson, J., Akermann, O., Barry, D.A., Rossi, L., 2014. Non-contact assessment of COD and turbidity concentrations in water using diffuse reflectance UV-Vis spectroscopy. Environmental Science: Processes & Impacts 16, 1897. https://doi.org/10.1039/C3EM00707C

[8] Hoppe, H., Fricke, K., Kutsch, S., Massing, C., Gruber, G., 2016. Von Daten zu Werten – Messungen in Entwässerungssystemen. Aqua & Gas 96, 26–31.

[9] https://www.endress.com/en/field-instruments-overview/measurement-technologies/smart-instrumentation-heartbeat-technology

3. SELECTION OF 8 INNOVATIVE TECHNOLOGIES FOR URBAN DRAINAGE RESEARCH AND PRATICE

To select a list of suitable sensors and digital technologies for testing in Task 6.1.2., we applied a three-phase strategy. First, we compiled a long list, second, narrowed it down to the 15 most promising sensors and then selected 8 for intensive testing. The process was led by INSA and Eawag who involved the partners UDC, UoS and Deltares. As planned, the partners IKT, GRAIE, AaU and EURO were not involved. External stakeholders, such as utilities or consultants were only involved through bilateral discussions with the individual partners.

In the first phase, each of the partners performed an internal review of the potential sensors of interest. As described in the proposal document, the sensors should focus on better technologies i) to monitor water quality and emerging pollutants, such as pesticides, PHA, Heavy-Metals and micro-plastics, ii) to manage sediments in UDS, and iii) to manage assets of both centralized and decentralized systems.

As guiding principles, the project partners base this sensor review on at least one of the following goals: i) low-cost, ii) low-maintenance, iii) potential to provide new data, either with new parameters or with a higher spatio resolution, iv) potential to observe emerging pollutants, and v) potential to deliver data to face actual or foreseeable challenges in research or practice.

By 09/2021 this first phase yielded the full list of 55 measurement devices (Table 8) and digital technologies, where ca. 30% concerned sensors to monitor rainfall-runoff, 60% were related to water quality monitoring and 10% concerned “Other” technologies (Figure 2, left), such as IoT data transmission or energy harvesting devices for underground infrastructures, which would facilitate ubiquitous sensing through energy self-sufficient monitoring systems.

Second, Eawag and INSA performed a collaborative ranking of the sensors regarding a) the potential of scientific novelty, b) the estimated TRL (Figure 1) and c) the practical feasibility to test the sensor, which basically included the cost for acquiring the sensor for testing and the current availability. Based on those criteria, we classified the 55 sensors in three categories to express the perceived benefits for the Co-UDlabs objectives as “high”, “medium” and “low”. The result of this was a list which only contained 15 pre-selected “sensors” and no “Other“ technologies anymore (Figure 2, right).

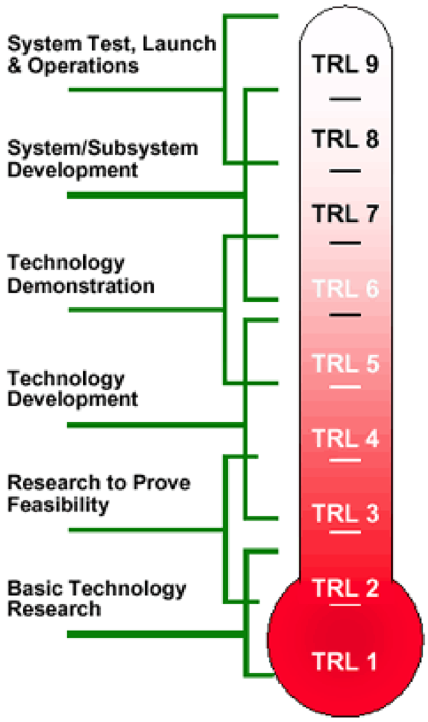
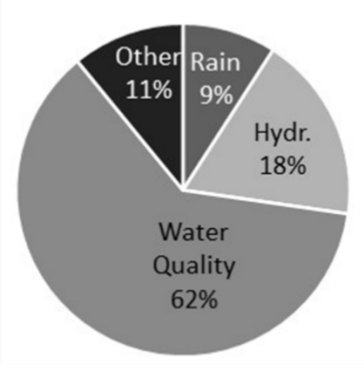
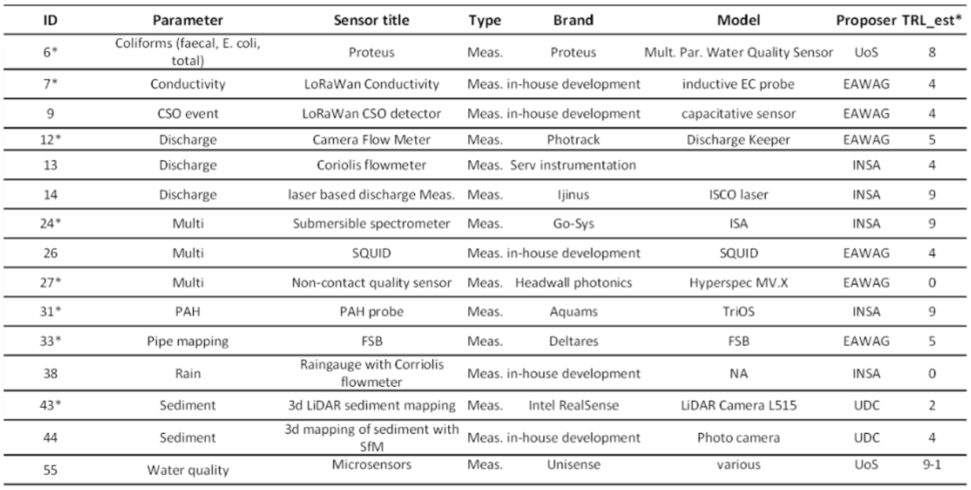


Figure 1: In our review, we used the TRL as a proxy to describe whether a promising sensor is more suited for research (low TRL) or practical applications (high TRL). Here, TRL 1 also comprises level 0, when no testing has been performed yet (source: Wikipedia[10]).





ID	Parameter	Sensor title	Type	Brand	Model	Proposer	TRL_est*
6*	Coliforms (faecal, E. coli, total)	Proteus	Meas.	Proteus	Mult. Par. Water Quality Sensor	UoS	8
7*	Conductivity	LoRaWan Conductivity	Meas.	in-house development	inductive EC probe	EAWAG	4
9	CSO event	LoRaWan CSO detector	Meas.	in-house development	capacitative sensor	EAWAG	4
12*	Discharge	Camera Flow Meter	Meas.	Photrack	Discharge Keeper	EAWAG	5
13	Discharge	Coriolis flowmeter	Meas.	Serv instrumentation		INSA	4
14	Discharge	laser based discharge Meas.	Meas.	Ijinus	ISCO laser	INSA	9
24*	Multi	Submersible spectrometer	Meas.	Go-Sys	ISA	INSA	9
26	Multi	SQUID	Meas.	in-house development	SQUID	EAWAG	4
27*	Multi	Non-contact quality sensor	Meas.	Headwall photonics	Hyperspec MV.X	EAWAG	0
31*	PAH	PAH probe	Meas.	Aquams	TriOS	INSA	9
33*	Pipe mapping	FSB	Meas.	Deltares	FSB	EAWAG	5
38	Rain	Raingauge with Corriolis flowmeter	Meas.	in-house development	NA	INSA	0
43*	Sediment	3d LiDAR sediment mapping	Meas.	Intel RealSense	LiDAR Camera L515	UDC	2
44	Sediment	3d mapping of sediment with SfM	Meas.	in-house development	Photo camera	UDC	4
55	Water quality	Microsensors	Meas.	Unisense	various	UoS	9-1

Figure 2, left: The suggested sensors mostly concerned water quality, but also other variables, right: Intermediate list of pre-selected sensors the final selection is labelled with a star. The full list of sensors and further information is given in the Appendix.

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[10] https://en.wikipedia.org/wiki/Technology_readiness_level#European_Commission_definition

Table 1: Preferences of the Co-UDlabs partners for TESTING the 8 selected Sensor systems

ID	Parameter	Sensor title	UDC	INSA Lyon	EAWAG	UoS	Delt.	Sum	Mean
6*	Coliforms (faecal, E. coli, total)	Proteus	3	1	1	3	0	8	2
7*	Conductivity	LoRaWan Conductivity	3	3	3	1	0	10	2.5
12*	Discharge	Camera Flow Meter	3	3	3	1	0	10	2.5
24*	Multi	Submersible spectrometer	3	2	3	1	0	9	2.25
27*	Multi	Non-contact quality sensor	3	3	4	1	0	11	2.75
31*	PAH	PAH probe	3	3	1	1	0	8	2
33*	Pipe mapping	FSB	1	3	2	2	4	12	2.4
43*	Sediment	3d LiDAR sediment mapping	2	4	1	1	3	11	2.2

Interest in testing the selected sensors is expressed on the following scale: 0= none, 1= curious, 2= commit to assist in testing, 3= commit to lead a test, 4: commit to develop a novel sensor.

In the third phase, each partner expressed his or her interest in testing a particular sensor in four categories from “not interested” (0) to “willing to develop” a novel sensor (4). The final selection was made by averaging all positive scores (Table 1). In a final step, the selected sensors were validated with the Co-UDlabs management board.

In summary, we achieved a satisfactory balance between monitoring technology with potential to advance urban drainage research and technology which can directly deliver added value to practitioners. Of the 8 selected, 4 sensors with a low TRL were chosen, for which only conceptual studies exist or which are currently being developed at the partners, e.g., available as prototypes. On the other end of the spectrum, 3 sensors have a TRL of 8 or higher, which means that, if tests are successful, they could readily be integrated in new monitoring services

4. DESCRIPTION OF SELECTED TECHNOLOGIES AND ENVISIONED TESTS IN THE CO-UDLABS INFRASTRUCTURES AND EXTERNAL PARTNERS

In this section, we describe the selected sensors and give required background information, e.g., technical specifications and fields of application. We will also give a perspective on potential challenges, details of the envisioned testing procedures and the expected benefit for the Co-UDlabs project.

4.1. COLIFORMS (PROTEUS INSTRUMENTS)

ID: 6, TRL: 8, Lead tester: James Shucksmith, University of Sheffield

Understanding the levels of bacteria in surface waters and urban drainage systems is important for meeting compliance with bathing water regulations as well as understanding risks to potable water supply. Bacterial characterization of surface waters is currently conducted by the collection of discrete water quality sampling, and subsequent laboratory analysis. Capturing water quality dynamics is therefore difficult using current methodologies[11].

The Proteus Coliform sensor utilizes a calibrated fluorescence sensor to infer levels of total coliforms and *E. coli* in rivers/drainage systems in real time. This would have benefits in terms of water quality model validation as well as direct practical applications such as bathing water status alerts, environmental impact assessment and real time control of urban drainage and drinking water abstraction systems.

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[11] Jamal R., Weidhaas J. Temporal Physiochemical and Bacteriological Variability in an Urban Stream and Implications for Compliance Monitoring (2022) Journal of Environmental Engineering (United States), 148 (5), DOI:10.1061/(ASCE)EE.1943-7870.0001992

However, to date, there is a lack of testing data to verify the performance of the technology, its ability to identify bacterial impacts from storm overflows/runoff or reference tests vs established methods such as plate counts.

Expected results for the Co-UDlabs project

Co-UD labs has access to a currently installed Proteus sensor in the River Leam, UK currently being trialed as part of a project with a UK water company Severn Trent Water. For this activity the project will monitor E.coli reading from the sensor over the installation period (18 months). During this period, we will collect several water quality samples during both low flow periods as well as during/after rainfall events, when higher peaks of E.coli are anticipated. These samples will be analyzed in the Severn Trent Water Quality Laboratory according to current UK regulatory standards[12]. We aim to collect samples during 4-5 rainfall events and well as one low flow event, at hourly temporal resolution over a 12-month period. One of these events will be used for sensor calibration purposes, with data from the remaining events to independently verify the sensor performance. We will use standard statistical criteria to quantify the agreement between Proteus data and reference data during all the events collected. We will also report on the general performance of the system when deployed in field environments, including reliability, maintenance and calibration requirements.

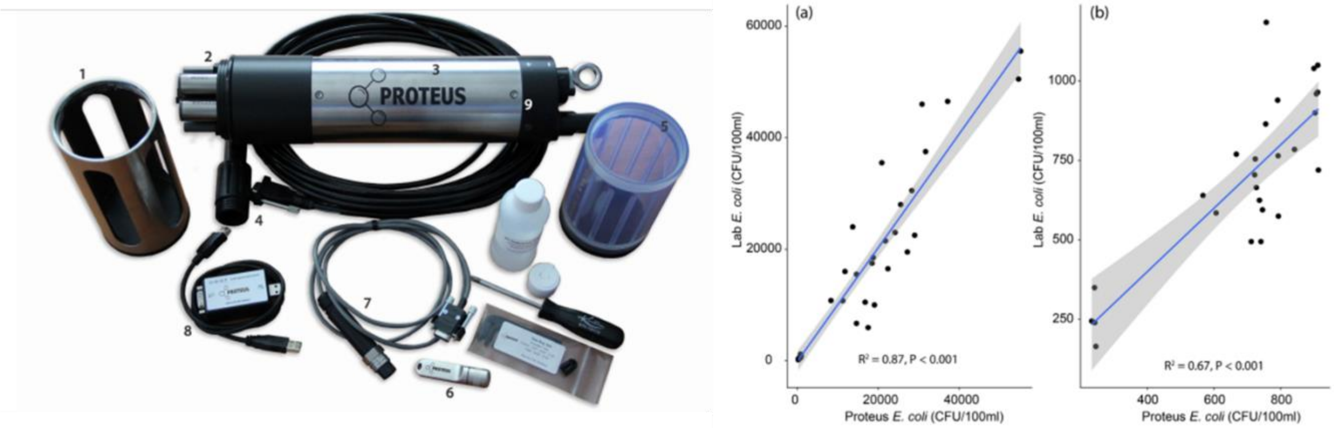

Figure 3, left: Proteus optical sensor for real-time coliform measurements based on in-situ fluorescence. Right: example of the relationship between the Proteus and laboratory measurements for a study in the River Lagan for a) all samples and b) low concentrations (source: RShydro[13]).

Table 2: Proteus mechanical, optical and physical specifications

Proteus specifications	
Dimensions	OD 76 mm L 460 mm
Weight	1.36 Kg
Operating range	-5° C - 50° C
Depth rating	200 m
Supply voltage range	5-15 Vdc
Signal output	SDI 12 & RS232 (Ethernet, TCP-IP, modbus, 4-20mA & re- lays with optional controller (AC or DC).
Communications	RS232/ Bluetooth

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[12] EN ISO 9308-1:2014 - Water quality - Enumeration of Escherichia coli and coliform bacteria - Part 1: Membrane filtration method for waters with low bacterial background flora (ISO 9308-1:2014)

[13] https://www.rshydro.co.uk/water-quality-monitoring-equipment/water-quality-testing-equipment/multiparameter-water-quality-sonde/proteus-bod-multiparameter-water-quality-meter/

Sample rate	1 Hz
Internal memory	4 MB; >1,000,000 readings
Warranty	12 - 24 months
Fluorometer specifications	
Excitation (nm) ± bandpass (nm) Exmission (nm) ± bandpass (nm)	285 ± 10 350 ± 55
Detection limit (ppb)	3.00*
Dynamic range (ppb)	0 – 20000*
Accuracy	±1% of reading (0 – 10000 ppb)
Coliform resolution (CFU/100ml)	0.1
Temperature compensation	Automatic (flexible- user defined)
Turbidity sensor specifications	
Turbidity range	0 -3000 NTU
Accuracy	0- 600 NTU (±1%) / 600 -3000 NTU (±2%)
Temperature compensation	Automatic (fixed)
Temperature sensor specifications	
Temperature range	-5° C - 50° C
Accuracy	± 0.1 ° C

4.2. ULTRA LOW-POWER CONDUCTIVITY PROBE WITH IOT DATA TRANSMISSION (EAWAG)

ID: 7, TRL: 4, Lead tester: Jörg Rieckermann, Eawag

Background information and advantages of the sensing system

The electrical conductivity (EC) is directly related to the concentration of ions in the water[14]. These conductive ions come from dissolved salts and inorganic materials, which makes EC an important water quality parameter. Typically, in wastewater applications, it is often used as a proxy for pollution[15] and has been used to investigate urban stormwater pollutant concentrations, loads, dynamics and intra-event fluxes. For applications in sewer systems, the biggest advantage of EC over more targeted analytical methods is the high temporal resolution.

In general, EC can be measured with conductive and inductive systems. Our experience showed that conductive systems are rather unsuitable for the harsh environmental conditions in sewers. By using electrodes, corrosion and other deposits form, which falsify the measurement result. Better alternatives are sensors that use an inductive measuring principle, which is much less susceptible to contamination. However, inductive conductivity sensors usually require fixed installations grid power supply. So far, autonomous operation over a longer period, supplied with batteries, is currently not possible with commercially available products[16].

For widespread applications across an entire wastewater system, sensor and data transmission technologies using low-power and IoT data transmission, such as LoRaWaN, would be desirable. To close this gap, Eawag and HSR have developed a Low-Power Inductive Conductivity Monitor (LPICM)[16], which has the following advantages over existing conductivity monitoring systems:

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[14] Wetzel, R. G. (2001). Limnology: Lake and River Ecosystems (3rd ed.). San Diego, CA: Academic Press.

[15] Métadier, M., Bertrand-Krajewski, J.-L., 2012. The use of long-term on-line turbidity measurements for the calculation of urban stormwater pollutant concentrations, loads, pollutographs and intra-event fluxes. Water Research, Special Issue on Stormwater in urban areas 46, 6836–6856. https://doi.org/10.1016/j.watres.2011.12.030

[16] Grab, T., Barbisch, L., 2018. Magnetisch-induktive Leitfähigkeitsmessung. University of Applied Sciences Rapperswi (HSR).

- low power: It can take a measurement of the conductivity and temperature of a liquid medium every 15 minutes with two 18650er Li-Ion AA batteries for a year or more (Figure 4, left).
- Wireless data transfer via LoRaWAN radio module and permanent storage on a SD card
- Open platform to ensure that future changes can be made easily and uncomplicatedly. A serial interface was also implemented in the prototype so that the measured values can be read out via a Matlab GUI.
- Custom CAD-designed shield to protect against sensor clogging (Figure 4, middle)

Potential drawbacks concern the comparably long response time of the integrated temperature sensor of about 5 minutes, due to the massive casing sensor head. Also, the sensor has been tested sporadically, but long-term results in various settings are lacking.

Figure 4, left: the first prototype of the low-power inductive conductivity monitor (LPICM) based on a commercial InPro7250 sensor (Mettler-Toledo, CH). Middle: The sensor with a custom-made clogging protection. Right: submerged LPICM during preliminary field tests at Lenzburg (CH)

Table 3: Sensor specifications of the low-power inductive conductivity monitor

Measuring range	0 - 2.000 mS/cm
Uncertainty of measurement	ST: # (0.5% of the value + 25 uS)
	HT:* (0.5% of the value + - I uS)
Cell factor nominal	2.175
Transmission factor	120
Temperature sensor	Pt 1000
Response time Pt 1000 (t90)	ca. 5 min

The testing of the LPICM during Co-UDlabs Task 6.1 will assess the performance of this device in 2-3 locations in real urban drainage systems using real wastewater and stormwater, considering different cross-sections, flow velocities and water depths. In preparation, tests in the HALL will be used to compare the performance with reference instrumentation, e.g., WTW tetracon 925 will be performed. Field tests in the UWO infrastructure are planned for 6-18 months. In addition, further tests with the utilities of Zug (CH) and Lenzburg (CH) are planned.

Expected results for the Co-UDlabs project

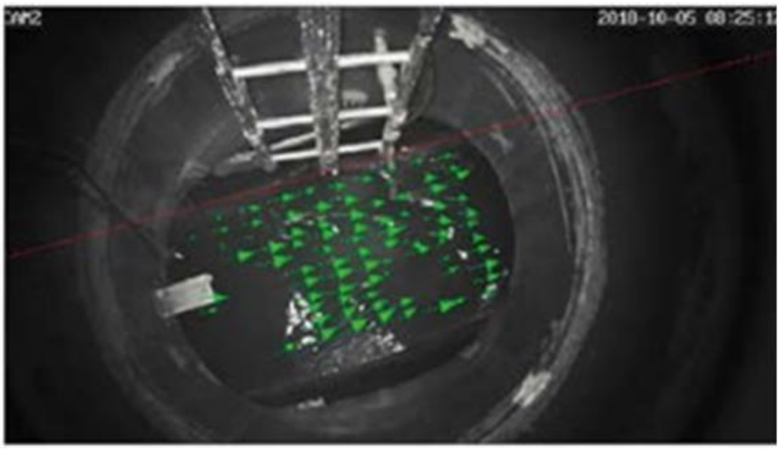
The results of the tests will be used to assess the potential for widespread spatial monitoring. Detailed Spatio-temporal monitoring with many sensors is important because further progress in knowledge and modelling of urban wet weather pollutant loads and pollutographs will require more detailed analyses of spatial variability and continuous time series rather than the traditional single event approach[14]. Also, concrete needs for developments to the next TRL level will be provided to support commercialization.

4.3. CAMERA FLOW METER (PHOTRACK)

ID: 12, TRL: 5, Lead Tester: Juan Naves, University of A Coruña

Operation and planning of sewer networks and wastewater treatment plants, as well as the fulfilment of legal obligations require knowing the volumetric flow and pollutant loads. Standard methods for flow measurements include the average velocity measurement with acoustic sensors, the so-called Dopplers, which have limitations in low flow conditions, need to be in contact with the fluid, can be affected by solids transported by the flow and require an installation inside the sewer. New non-intrusive methods such as imaging techniques may facilitate the acquisition of flow measurements along sewer networks and other urban drainage assets, which can help in the decision-making process regarding the operation of sewers and WWTP during dry and wet periods.

During the last few years, several image-based methods for measuring the surface velocity in rivers and canals have been proposed and successfully tested[17,18]. However, its implementation in sewers and water treatment plants has not yet started to be commercialized. In this context, Photrack AG[19] is an SME whose core business is discharge measurements of rivers, streams, irrigation furrows with webcams and smartphones.



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[17] Tauro, F., Petroselli, A., and Grimaldi, S.: Optical sensing for stream flow observations: A review, J. Agr. Eng., 49, 199–206. https://doi.org/10.4081/jae.2018.836, 2018

[18] Manfreda, S., McCabe, M. F., Miller, P. E., Lucas, R., Pajuelo Madrigal, V., Mallinis, G., Ben Dor, E., Helman, D., Estes, L., Ciraolo, G., and Müllerová, J.: On the use of unmanned aerial systems for environmental monitoring, Remote Sens., 10, 641, https://doi.org/10.3390/rs10040641, 2018.

[19] http://www.photrack.ch/

Figure 5: Camera Flow Meter (Photrack AG) and preliminary map of surface velocities obtained from a fixed camera in a manhole at the HALL[20] infrastructure (Eawag).

The company has developed an image-based technology to measure the volumetric flow from surface velocities and depths. The system has been successfully brought into operational use in rivers[21], and these systems are currently being used and tested for example in Switzerland, Germany, Luxembourg, Spain, India, China, Canada or Tanzania. In addition, it has been preliminary tested in sewers giving promising results[22].

The sensor is used the continuous acquisition and storage of flow velocity profiles, water levels and flow rates in natural water streams, irrigation furrows and channels. The device consists of an IP-camera, an infrared beamer, and a measuring transducer with remote data transmission. The surface velocity profile is measured by means of an optical method called Surface Structure Image Velocimetry (SSIV), based on the cross-correlation technique, for capturing the flow velocity. The water level detection is carried out simultaneously by an image processing technique. The vertical velocity profile is obtained employing a mixing length model. Subsequently, the discharge is calculated directly on site. In general, a measurement process takes only 40 seconds. In addition to the digitized measured values, proof images are stored and can be transmitted to an FTP server via GPRS allowing the verification of results. No flow tracers are required for flow velocity detection since the software operates on visible moving surface structures, and it can also be used under a wide variety of lighting conditions. The sensor may be operated with a 12 V battery or a small solar panel.

Expected results for the Co-UDlabs project

The testing of Photrack's camera flow meter during Co-UDlabs Task 6.1 will assess the performance of this device in the field of urban drainage using real wastewater, considering different cross-sections, flow velocities and water depths, and also assessing the influence of bedload sediments on the estimation of flows. Tests will be performed under realistic but controlled and monitored conditions in the BENS facility[23], which is a facility operated by the University of A Coruña and offered within Co-UDlabs Transnational Access. The facility consists of a 10 m length and 0.8 m width metallic bench, where different sewer typologies can be installed, for studying sewer processes using real wastewater from the pre-treatment system of A Coruña WWTP with a maximum flow discharge of 30 L/s, variable slope and with the possibility of regulating water levels. In addition to surface velocities, water depths and estimated discharges, the experiments are expected to serve also to explore other potential data that could be estimated from images such as correlations between water colour and quality parameters or the presence of floats[24]. Finally, the results will be considered for the subsequent installation of the camera in a real sewerage network.

4.4. SUBMERSIBLE SPECTROPHOTOMETER ISA (GO-SYSTEMELEKTRONIK)

ID: 24, TRL: 9, Leader tester: Jörg Rieckermann, Eawag

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[20] https://co-udlabs.eu/access/research-facilities/hall/

[21] Peña-Haro, S., Carrel, M., Lüthi, B., Hansen, I. Lukes, R.. (2021). Robust Image-Based Streamflow Measurements for Real-Time Continuous Monitoring. Frontiers in Water 3: 175. https://doi.org/10.3389/frwa.2021.766918.

[22] Peña-Haro, S., Carrel, M., Lüthi, B., Wang, L., Dicht, S. and Leitão, J. P. (2019). Abflussmessungen Mittels Videos. Einsatz von Webcams Und Smartphones. (Sewer discharge measurements by means of videos. Use of webcams and smartphones). Aqua&Gas, 2019.

[23] https://co-udlabs.eu/access/research-facilities/bens/

[24] Moreno-Rodenas, A. M., Duinmeijer, A., & Clemens, F. H. (2021). Deep-learning based monitoring of FOG layer dynamics in wastewater pumping stations. Water Research, 202, 117482.

In-situ UV-VIS spectrometry with submergible sensors has already been an established method for about 20 years for online pollution monitoring in urban drainage systems. Especially for organic pollutants (BODeq, CODeq, TOCeq), Nitrate (NO3_eq), and particulates (Turbidity_eq)[25]. As submersible spectrophotometers observe the adsorption spectrum of the media, without wet chemical reactions, the monitoring principle is based on correlations to the water quality parameter of interest. Specifically, chemometric models such as PLS are applied to the value pair of absorption spectra and reference values. The most suitable wavelength combination for the respective water matrix on-site is identified[26]. Bottlenecks of the method are that the sensor must be adjusted to the wastewater characteristics of the monitoring site to deliver appropriate results[26,27]. Also, the spectral data are highly correlated, i.e., several adjacent wavelengths are virtually affected in the same way by changes in the wastewater composition. Therefore, the workhorse of retrieving pollutant equivalents from submersible spectrophotometers is the PLS regression[24], which already includes a dimensionality reduction. Several investigations to improve the precision of such spectrophotometers with advanced data-driven methods have not been successful, which might hint to a lack of information between the observations and ground truth observations.

The submersible spectrophotometer ISA is particularly interesting, because:

- the parameters Ammonium (NH4_eq) and phosphate (PO4_eq) are not yet part of estimation with this method, because they do not absorb light in the UV-VIS range. Yet, they are particularly relevant for integrated assessment of sewers, WWTP and receiving waters.
- It has a variable path length from 0.5 - 20mm, which means that potentially one sensor platform can be used for stormwater, wastewater and surface water applications by a utility or consultancy.
- It provides full access to all spectral data, and provides chemometric models to aid the customized calibration to on-site conditions
- It is suitable for remote monitoring in UDS, because it is available in an ATEX version and as a mobile unit, which can operate on batteries for several days

The sensor measures adsorption spectra in the UV/VIS wavelength range from 200 nm to 708 nm with a resolution of 2 nm and a minimum measurement interval of 60 s. It has a Xenon flash lamp as a light source. Current experiences with applications in wastewater and surface waters are promising (Figure 6, right). For example, the ISA was of special interest for the project INTCATCH to implement the new developments for the estimation of NH4_eq and PO4_eq in surface waters with this technology[28]. The evaluation has been rather favorable, especially regarding measuring diluted wastewater, therefore it is most possibly also applicable for stormwater monitoring. Although indoor calibration and tests in INTCATCH were successful, field trials in the Danube River were less successful, apparently due to limited time for calibration, e.g., collecting reference spectra. The goal of the tests is to assess the reliability of the sensor in various sewer applications.

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[25] Langergraber, G., Fleischmann, N., Hofstadter, F., 2003. A multivariate calibration procedure for UV/VIS spectrometric quantification of organic matter and nitrate in wastewater. Water Science and Technology 47, 63–71.

[26] Lepot, M., Torres, A., Hofer, T., Caradot, N., Gruber, G., Aubin, J.-B., Bertrand-Krajewski, J.-L., 2016. Calibration of UV/Vis spectrophotometers: A review and comparison of different methods to estimate TSS and total and dissolved COD concentrations in sewers, WWTPs and rivers. Water Research 101, 519–534. https://doi.org/10.1016/j.watres.2016.05.070

[27] Jacobs, S.R., Weeser, B., Rufino, M.C., Breuer, L., 2020. Diurnal Patterns in Solute Concentrations Measured with In Situ UV-Vis Sensors: Natural Fluctuations or Artefacts? Sensors 20, 859. https://doi.org/10.3390/s20030859

[28] https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c43504d2&appId=PPGMS

Expected results for the Co-UDlabs project

The testing of the ISA will assess the performance of this device in the laboratory and two-three full scale applications. Tests in the HALL[29] at Eawag will be used to compare the performance with an ISE sensor WTW AmmoLyt®Plus 700 IQ and ICP laboratory measurements as a reference. Field tests at the HALL infrastructure are planned for 3-6 months. In addition, further tests are envisioned with the utilities of Olten (CH) and Dübendorf (CH). The results of the tests will be used to assess the potential for determining NH4 loads in wastewater systems. This is particularly important for the integrated assessment of sewers and WWTPs, and pollution-based Real-Time Control of integrated wastewater systems.

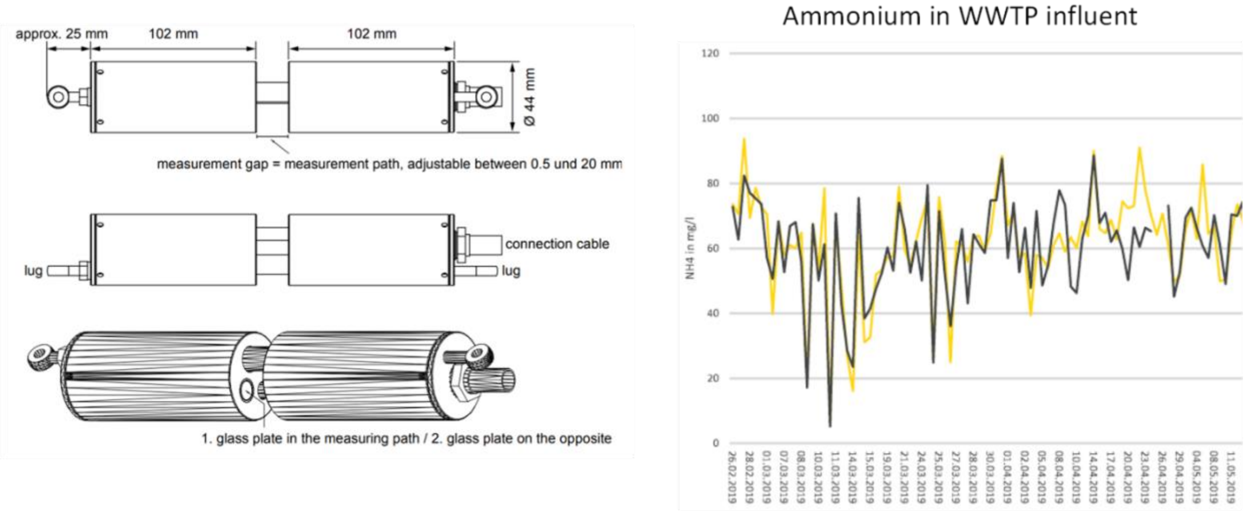
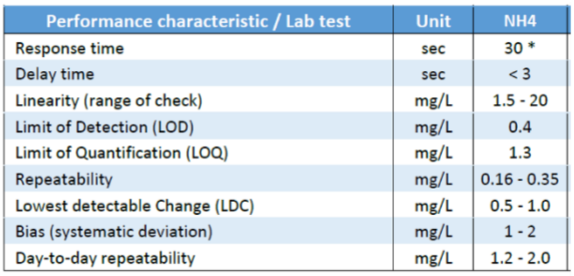
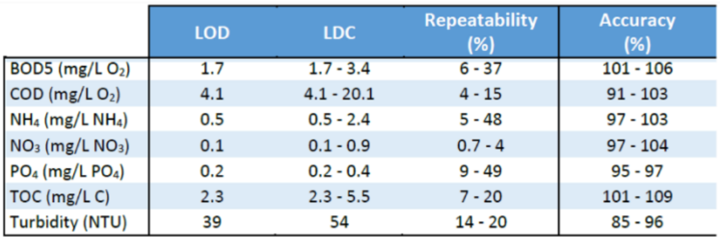


Figure 6, left: sensor head of the "Intelligent Spectral Analyzer" (ISA, GoSYS), which features a variable path length, full access to the recorded spectra and powerful tools for custom calibration, e.g., to retrieve equivalents of sulfide, ammonia and orthophosphate based on correlations to observed adsorption spectra. Right: example of a monitoring campaign in raw wastewater and comparison to laboratory results (adapted from GoSYS).

Table 4: performance characteristics from Laboratory test in the INTCATCH project with diluted wastewater



Performance characteristic / Lab test	Unit	NH4
Response time	sec	30 *
Delay time	sec	< 3
Linearity (range of check)	mg/L	1.5 - 20
Limit of Detection (LOD)	mg/L	0.4
Limit of Quantification (LOQ)	mg/L	1.3
Repeatability	mg/L	0.16 - 0.35
Lowest detectable Change (LDC)	mg/L	0.5 - 1.0
Bias (systematic deviation)	mg/L	1 - 2
Day-to-day repeatability	mg/L	1.2 - 2.0



	LOD	LDC	Repeatability (%)	Accuracy (%)
BOD5 (mg/L O_2)	1.7	1.7 - 3.4	6 - 37	101 - 106
COD (mg/L O_2)	4.1	4.1 - 20.1	4 - 15	91 - 103
NH_4 (mg/L NH_4)	0.5	0.5 - 2.4	5 - 48	97 - 103
NO_3 (mg/L NO_3)	0.1	0.1 - 0.9	0.7 - 4	97 - 104
PO_4 (mg/L PO_4)	0.2	0.2 - 0.4	9 - 49	95 - 97
TOC (mg/L C)	2.3	2.3 - 5.5	7 - 20	101 - 109
Turbidity (NTU)	39	54	14 - 20	85 - 96

(adapted from[28])

4.5. PAH PROBE (AQUAMS)

ID: 12, TRL: 5, Lead tester: Mathieu Leport, INSA

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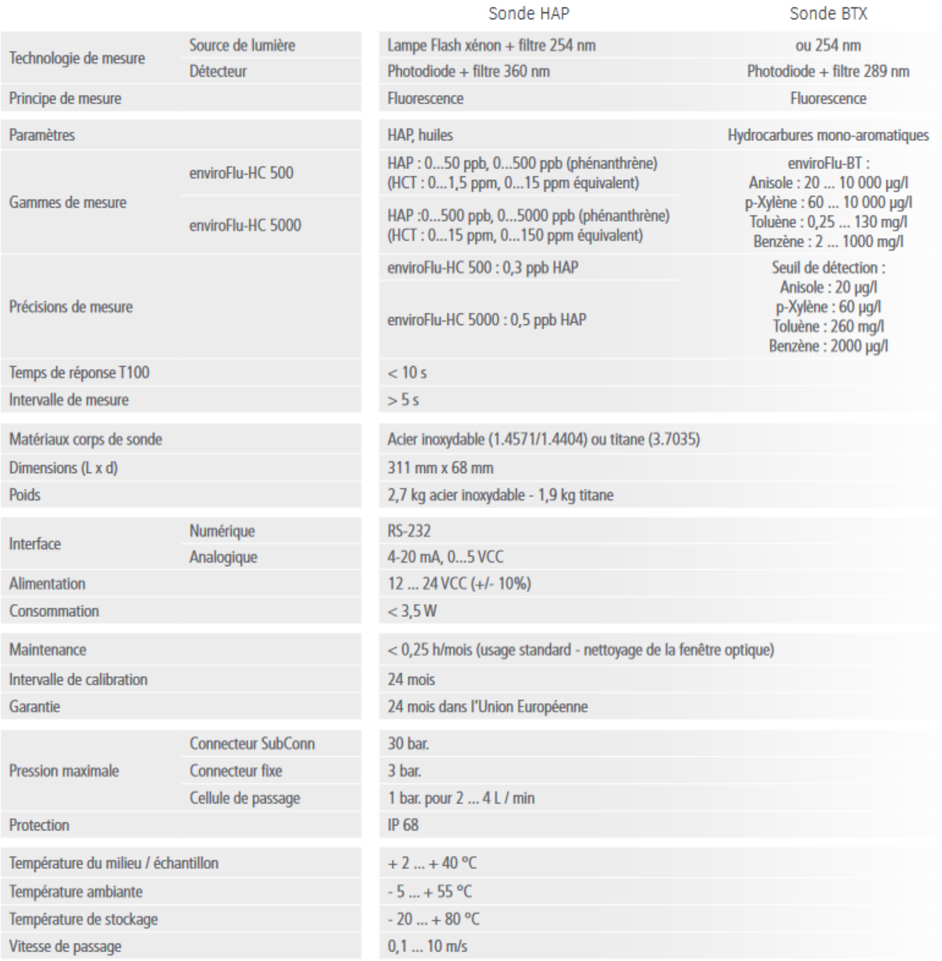
[29] https://co-udlabs.eu/access/research-facilities/hall/

PAHs are emerging pollutants for water bodies. Generated by human activities, they have major impacts on water quality, especially for the environment and drinkable water production. Mainly coming from runoff processes, PAHs can be directly emitted into surface water or water table if there is not any basic pre-treatment downstream of the stormwater system. Traditionally, PAHs were measured on samples in the laboratory and continuous measurements remained unfeasible.

The proposed sensor measures a total PAH concentration using fluorescence and without any laboratory analysis and can achieve a measurement frequency of 5 seconds. Depending on the internal settings, the measuring range can either be 0 – 50 ppb or 0 – 500 ppb, which covers the PAH concentrations found in the literature review (Table 5).



		Sonde HAP	Sonde BTX
Technologie de mesure	Source de lumière	Lampe Flash xénon + filtre 254 nm	ou 254 nm
	Détecteur	Photodiode + filtre 360 nm	Photodiode + filtre 289 nm
Principe de mesure		Fluorescence	Fluorescence
Paramètres		HAP, huiles	Hydrocarbures mono-aromatiques
Gammes de mesure	enviroFlu-HC 500	HAP : 0...50 ppb, 0...500 ppb (phénanthrène) (HCT : 0...1,5 ppm, 0...15 ppm équivalent)	enviroFlu-BT : Anisole : 20 ... 10 000 µg/l p-Xylène : 60 ... 10 000 µg/l Toluène : 0,25 ... 130 mg/l Benzène : 2 ... 1000 mg/l
	enviroFlu-HC 5000	HAP :0...500 ppb, 0...5000 ppb (phénanthrène) (HCT : 0...15 ppm, 0...150 ppm équivalent)	
Précisions de mesure		enviroFlu-HC 500 : 0,3 ppb HAP	Seuil de détection : Anisole : 20 µg/l p-Xylène : 60 µg/l Toluène : 260 mg/l Benzène : 2000 µg/l
		enviroFlu-HC 5000 : 0,5 ppb HAP	
Temps de réponse T100		< 10 s	
Intervalle de mesure		> 5 s	
Matériaux corps de sonde		Acier inoxydable (1.4571/1.4404) ou titane (3.7035)	
Dimensions (L x d)		311 mm x 68 mm	
Poids		2,7 kg acier inoxydable - 1,9 kg titane	
Interface	Numérique	RS-232	
	Analogique	4-20 mA, 0...5 VCC	
Alimentation		12 ... 24 VCC (+/- 10%)	
Consommation		< 3,5 W	
Maintenance		< 0,25 h/mois (usage standard - nettoyage de la fenêtre optique)	
Intervalle de calibration		24 mois	
Garantie		24 mois dans l'Union Européenne	
Pression maximale	Connecteur SubConn	30 bar.	
	Connecteur fixe	3 bar.	
	Cellule de passage	1 bar. pour 2 ... 4 L / min	
Protection		IP 68	
Température du milieu / échantillon		+ 2 ... + 40 °C	
Température ambiante		- 5 ... + 55 °C	
Température de stockage		- 20 ... + 80 °C	
Vitesse de passage		0,1 ... 10 m/s	

Table 5: Specifications of the EnviroFlu HC-500 (Aquams)

Expected results for the Co-UDlabs project

During the Co-UD labs project, we expect to provide outputs from a full validation test series of this probe. The main idea of the tests is divided into two parts: i), establish a calibration function between the concentrations recorded by the probe and the ones analyzed in the laboratory and then ii) install the probe in the field (stormwater system for INSA and WWTP inlet for UDC) in order to record time series for PHA concentrations. When analyzing the results of those 4 campaigns, the robustness of this technology and this particular probe will be tested.

Figure 7: AQUMS Trios PAH fluorometer probes

4.6. HYPERSPECTRAL CAMERA MV.X (HEADWALL PHOTONICS)

ID: 27, TRL: 0, Testing Leader: Jörg Rieckermann, Eawag

As discussed in section 4, continuous pollution monitoring in sewers is usually performed with submerged spectrometer probes[26]. These operate in the UV-VIS range of 200-800nm range and require site-specific adjustment by means of “local calibration” to reference lab measurements. Typical observation errors are 30% for so-called COD equivalents[30].

Unfortunately, submerged online probes quickly deteriorate in the harsh sewer environment[30,31]. This means that these probes require a lot of maintenance, e.g., cleaning with HCl solutions, and observations can depend on the positioning of the sensor and lighting conditions[26]. Consequently, they are rarely applied in practical applications, which require reliable observations without excessive maintenance. Therefore, recent advances regarding non-contact monitoring of wastewater pollution proxies seem very promising[7,32]. In addition, remote sensing has been continuously improving and today, even hyperspectral cameras are affordable.

In this Task, we are going to test the performance of a hyperspectral camera system, the Headwall MV.X (Figure 8, left). It is a compact, dust-proof watertight hyperspectral system designed specifically for advanced machine vision and process analytical applications. In comparison to spectrophotometers, hyperspectral cameras seem to be very promising for non-contact wastewater monitoring, because they measure spectral “cubes”, e.g., 2D line-scan images with a spectrum for each pixel. Also, they observe a comparably large area of several tens of square centimeters compared to a few cubic millimeters for the optical windows of the submerged probes. We chose the MV.X sensor because of the following advantages over comparable imaging devices:

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[30] Gruber, G., Winkler, S., Pressl, A., 2005. Continuous monitoring in sewer networks an approach for quantification of pollution loads from CSOs into surface water bodies. Water Science and Technology 52, 215–223. https://doi.org/10.2166/wst.2005.0466

[31] Bourgeois, W., Burgess, J.E., Stuetz, R.M., 2001. On-line monitoring of wastewater quality: a review. Journal of Chemical Technology & Biotechnology 76, 337–348. https://doi.org/10.1002/jctb.393

[32] Mullins, D., Coburn, D., Hannon, L., Jones, E., Clifford, E., Glavin, M., 2018. A novel image processing-based system for turbidity measurement in domestic and industrial wastewater. Water Science and Technology 77, 1469–1482. https://doi.org/10.2166/wst.2018.030

- It measures between 400 and 1000nm with a spectral resolution of 2nm and 1020 spatial bands.
- It is the only sensor on the market with IP67 protection
- It has advanced internal processing capabilities due to a powerful CPU and a user-friendly interface which facilitates custom calibration procedures for different monitoring locations and tasks

Because the sensing methodology for the MV.X has to be developed from scratch (Figure 2, right), will we first perform laboratory tests with different synthetic and natural wastewaters. We envision doing a test series of about 100 different wastewater samples. As a reference, we will use different lab analytical techniques from the HALL infrastructure, such as alyzers for DOC and TN, as well as ICP for Nitrite, Nitrate, and Orthophosphate. For turbidity, we will use a lab-bench turbidity meter (TL2350, Hach) as a reference.

Expected results for the Co-UDlabs project

The results of the tests will be used to assess the potential for determining pollutant loads in wastewater systems. The focus will be on organic pollution, e.g., COD or DOC and on particulate pollution, e.g., TSS. This is particularly important for the integrated assessment of sewers and WWTPs, and pollution-based Real-Time Control of integrated wastewater systems.

Figure 8, left: Hyperspectral line-scan camera MV.X, right: sensor during initial test measurements with synthetic wastewater at the HALL infrastructure at Eawag

Table 6: Specifications of the Hyperspec MV.X (Headwall Photonics)

Wavelength Range	400-1000 nm	Camera Sensor Technology	CMOS
Spatial Bands	1020	Memory, Storage	8GB RAM, 128GB SSD
Spectral Bands	340	Input Voltage	12-30V DC
Spectral Sampling	1.75 nm/pixel	Max Power Consumption	< 42 W
Spectral FWHM	6 nm	Dimensions (L x W x H)	255 x 136 x 136 mm / 10.0 x 5.4 x 5.4”
System F/#	f/2.5	Weight with 24 mm Lens	3 kg / 6.6 lb
Optical Design	Aberration-corrected concentric	Ingress Protection (IP)	IP66, IP67
Field of View (24mm focal lens)	Angular: 14.20°, Instantaneous: 0.014°	Operating Temperature Range	0 - 50°C / 32 - 122°F
Bit Depth	12 bit	Software	Web User Interface for system configuration and control. On-board classification modules available.

4.7. PIPE MAPPING FSB (DELTARES)

ID 33, TRL: 5, Testing Leader: Antonio Moreno Rodenas

Underground water infrastructure maps are still incomplete or erroneous in many European urban water systems[33]. One of the main challenges when dealing with mapping buried urban water assets is the inability to acquire accurate positioning data underground. This often introduces gross errors into hydraulic rainfall-runoff models, e.g., from wrongly connected pipes, erroneous diameters, and invert levels, which in turn leads to sub-optimal rehabilitation and maintenance planning[34].

Improving datasets for underground infrastructure is an often-costly endeavor requiring detailed inspection and access to the assets. Providing accurate positioning underground is challenging due to the attenuation of common navigation systems (GNSS) and due to the large errors produced by dead-reckoning inertial systems[35]. However, the combined use of inertial and visual odometry is a promising application to improve the accuracy in underground mapping[36].

This sensor prototype is a low-cost low-footprint platform that can be deployed either as a passive (i.e., transported with the pipe flow) or embedded in other equipment where positioning data is critical (e.g., inspection umbilical probes, robotic platforms etc.). The sensor relies on a stream of data comprising inertial motion units (IMUs), LIDAR (top distance meter) and imagery. These sensors are used as a simultaneous localization and mapping (SLAM) device by fusing data from the IMUs (which induce large errors in time) with distance and optical flow motions. By using external reference points (e.g., pipe diameter or pipe-joints/manholes) the device attempts to reconstruct the motion path and map the internal geometry of the pipe network.

The sensor consists of a low-cost embedded system containing a micro-computer, up to three consumer-grade 9DOF IMUs (acceleration, magnetic field and gyroscopes), a top distance fixed LIDAR (4-400 cm range) and a fisheye camera system, recording at >50 Hz. The system is initiated, controlled and performs data-transfer through a Wireless application. The device can be externally, or battery powered. A version of the hardware and software is available as a modular platform for fast prototyping. However, the stability of the hardware, and accuracy of the SLAM reconstruction is still not formally tested, being still of experimental nature. Deltares and INSA Lyon will collaborate to conduct a series of laboratory and field tests towards a better description of the performance of the device.

Expected results for the Co-UDlabs project

The tests will evaluate several aspects of the applicability of low-cost tracer-like inertial and camera sensors to retrieve pipe connectivity and geometry. First, we will aim at ascertaining the temporal stability of low-cost IMU sensors (e.g., BNO055) to provide coherent directions of travel in linear-like structures. This will include reviewing the error accumulation rate of accelerometer measurements under laboratory conditions, and also studying the effect of hard-soft iron magnetometer effects in underground structures with a field experiment. Secondly, we

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[33] F. Tscheikner-Gratl, 2015. Integrated approach for multi-utility rehabilitation planning of urban water infrastructure. PhD Thesis, Universitat Innsbruck.

[34] W. van Riel, 2016. On decision-making for sewer replacement. PhD thesis. TUDelft https://doi.org/10.4233/uuid:92b10448-795d-43ac-8071-d779af9d374d

[35] Manon Kok, Jeroen D. Hol and Thomas B. Schon (2017). " Using Inertial Sensors for Position and Orientation Estimation", Foundations and Trends in Signal Processing: Vol. 11: No. 1-2, pp 1-153.http://dx.doi.org/10.1561/2000000094

[36] Aitken, J. M., Evans, M. H., Worley, R., Edwards, S., Zhang, R., Dodd, T., ... & Anderson, S. R. (2021). Simultaneous localization and mapping for inspection robots in water and sewer pipe networks: A review. IEEE Access.

expect to be able to provide insights on camera angular and temporal resolution necessary (for FSB type sensors) to capture motion features (in-pipe velocity) that can be used to refine the IMU drift.

A dedicated laboratory experiment at the Deltare's hydraulic laboratory, consisting of an artificial pipe system of an approximately 15-meter long, 30 cm diameter pipe section with a 90-degree bend will be used to subject the FSB sensor to controllable motion and trajectories. Additionally, we plan to carry out a field experiment to explore the behavior under real conditions (e.g., hard-soft iron disturbances of the magnetometer in real systems). These two experiments carried out jointly by INSA Lyon and Deltares, aim at describing the applicability and possible improvements of an FSB-like sensor system for the reconstruction of underground pipe connectivity/geometry.

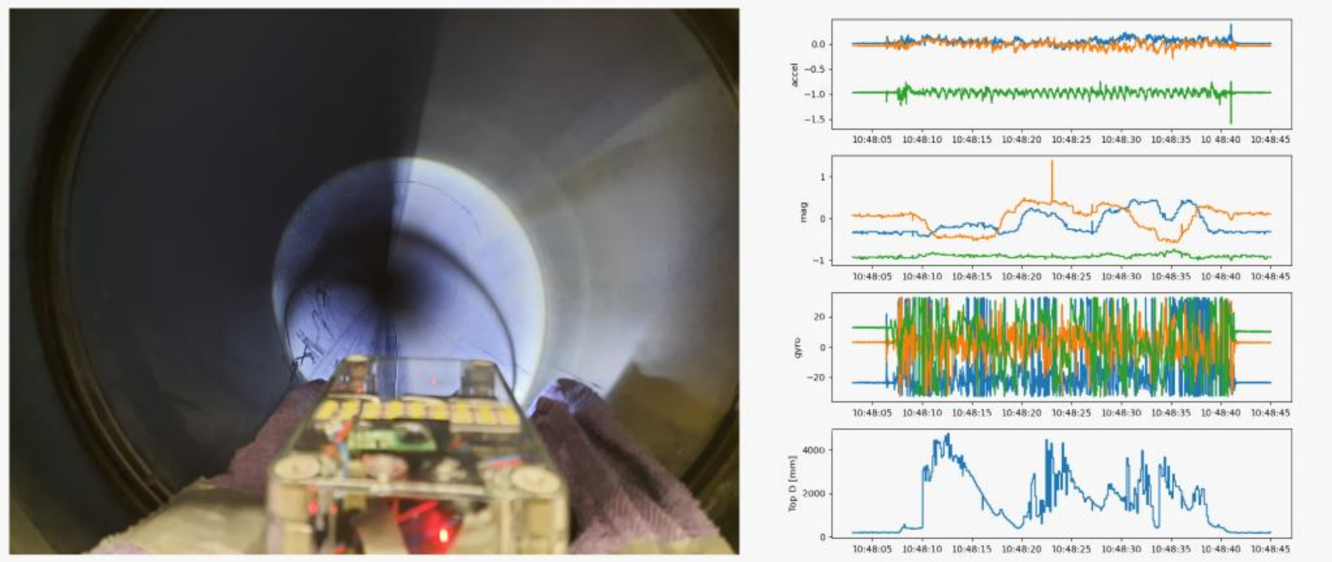

Figure 9, left: modular FSB prototype, right: IMU data stream:

4.8. 3D MAPPING OF SEDIMENT WITH LIDAR (INSA)

ID: 43, TRL: 0, Testing Leader: Mathieu Lepot, INSA

Sedimentation processes occur in most of UDS infrastructures, including the emerging SUDS. Monitoring these sediments is necessary to better understand sedimentation and erosion processes, since sediment deposits in such structures reduce their hydraulic capacities and available retention volumes priori infiltration. To optimize maintenance tasks, practitioners need to measure the remaining retention volume in SUDS. However, such measurements in blue/green or nature-based solutions such as SUDS are rather new, and no techniques has been yet developed or assessed.

In the literature, some technologies have been investigated regarding the measurement of deposited sediments or elevations maps in UDS. In recent studies submersible sonar[37] and photogrammetric techniques[38] have been applied successfully to monitor sediments bedloads in sewers. These methods compared the initial shape of the pipe, used

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[37] Lepot, M., Pouzol, T., Aldea Borruel, X., Suner, D., Bertrand-Krajewski, J.-L., 2017. Measurement of sewer sediments with acoustic technology: from laboratory to field experiments. Urban Water Journal 14, 369–377. https://doi.org/10.1080/1573062X.2016.1148181

[38] Regueiro-Picallo, M., Anta, J., Suárez, J., Puertas, J., Jácome, A., Naves, J., 2018. Characterisation of sediments during transport of solids in circular sewer pipes. Water Science and Technology 2017, 8–15. https://doi.org/10.2166/wst.2018.055

as reference, with the results obtained when sedimentation is produced to obtain sediment load volumes. On a larger scale, the same photogrammetric technique, named Structure from Motion, was also used in laboratory to obtain high resolution elevation map of the surface of a 36 m^2 urban drainage physical model[39]. The UDC research group also used the Intel® RealSense™ LiDAR Camera to measure high resolution 3D surface models of a laboratory facility of a T-intersection street of 100 m^2 with roofs, roads and pavements, which is the BLOCK[40] facility offered in the Co-UDlabs Transnational Access program. In these last studies, there were no sediment measurements, but the techniques (photogrammetry and LIDAR) demonstrated the accurate applicability of this kind of approach to larger areas.

The prototype we plan to design and build will use LIDAR to allow operators to estimate sedimentation in SUDS while using an aerial drone to conduct traditional labor-intensive topographic measurements on site. As the sensor is a prototype which still must be built, there are no visuals or specifications available yet. We do expect an accuracy of a few cm in each 3D dimension.

Expected results for the Co-UDlabs project

Once the design and the construction will have been done, the partners involved in those tests aim at delivering a proof of concept of such technologies with rough ideas on current limitations of such applications.

5. EXPECTED OUTCOME AND CONTRIBUTION TO THE OBJECTIVES OF CO-UDLABS

We expect that the direct outcome of the T6.1.1., the list of 8 sensors, is fundamental for our endeavors to evaluate improved instrumentation and new data sources for hydraulics, pollutant load monitoring and asset inspection of urban drainage systems.

The 8 selected sensors have a high potential to improve the management of UDS, in the short term (sensors with high TRL), as well as in the long-term, (sensor prototypes that have a low TRL, but a high potential to provide relevant information, e.g., on asset condition or pollutant proxies). As described in section 4, testing is planned in the lab, but for most sensors, continuous operation in real sewers with long durations of more than a year is envisioned. As the testing partly includes external partners, such as utilities, this long-term testing in various system and under different boundary conditions will be a unique body of knowledge on the reliability of the tested approaches and whether they are fit-for-purpose.

For the more research-oriented sensors with a lower TRL (e.g, non-contact water quality monitoring (ID 27) or 3D Lidar mapping), we mainly explore the applicability and possibilities of novel measurement techniques applied to urban drainage monitoring, and also identify key points to continue developing these sensors in the near future. We expect that our in-depth assessment in T6.1.2 will lead to 2-4 peer-reviewed scientific publications.

For the commercially available sensors with a high TRL, we expect that the in-depth testing and joint assessment will help to reveal bottlenecks and challenges, which are instrumental in improving UDS technology. In addition, we

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[39] Naves, J., Anta, J., Puertas, J., Regueiro-Picallo, M., Suárez, J., 2019. Using a 2D shallow water model to assess Large-Scale Particle Image Velocimetry (LSPIV) and Structure from Motion (SfM) techniques in a street-scale urban drainage physical model. Journal of Hydrology 575, 54–65. https://doi.org/10.1016/j.jhydrol.2019.05.003

[40] https://co-udlabs.eu/access/research-facilities/block/

expect that it will help the manufacturers to grow their customer base through the dissemination and networking activities in Co-UDlabs. Last, but not least, through our activities, SME involved in development of monitoring, might even be interested in adopting the suggested sensors with intermediate TRL (ID 7 – Ultra low-power conductivity probe) and thus spark innovation.

Regarding the contribution to overall Co-UDlabs goal and objective, the expected results from task 6.1.1. will directly support the objectives of WP6. Specifically, they will “identify and evaluate new sensors and technologies for hydrological and hydraulic variables, pollutant load monitoring and UD underground asset inspection” (O6.2), and “evaluate new methods […] to improve the evidence base for reliable and validated urban drainage monitoring data” (O6.3).

On a higher level, they will mostly contribute to “secure the long-term resilience and sustainability of urban drainage systems with the help of more robust, autonomous and interconnected smart monitoring techniques, and digital water data analysis tools.” (Main Objective 3). In addition, they will partly contribute to the Main Objective 2 by providing real-scale evidence that new techniques work.

Thus, the expected results will also have an important socio-environmental impacts and contribute to higher-level EU policy, because Technologies and the ‘hybrid grey and green infrastructure’ are Key Components for a Water Smart Society[3] in the Strategic Innovation and Research Agenda (SIRA) of the Water Europe platform. By this, it is fully aligned with the Horizon Europe vision[41], which aims for a sustainable, fair, and prosperous future for people and planet based on European values by (i) tackling climate change, (ii) helping to achieve Sustainable Development Goals and (iii) boosting the Union's competitiveness and growth.

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[41] Horizon Europe. The next R&I investment programme.

6. APPENDIX

TABLE 7: SHORT LIST OF 15 SENSORS

ID	Parameter	Sensor title	Type[1]	Brand	Model	Proposer	TRL$_{est}$[2]
6*	Coliforms (faecal, E. coli, total)	Proteus	Meas.	Proteus	Multi-par. Water Quality Sensor	UoS	8
7*	Conductivity	LoRaWan Conductivity	Meas.	in-house development	inductive EC probe	EAWAG	4
9	CSO event	LoRaWan CSO detector	Meas.	in-house development	capacitative sensor	EAWAG	4
12*	Discharge	Camera Flow Meter	Meas.	Photrack	Discharge Keeper	EAWAG	5
13	Discharge	Coriolis flowmeter	Meas.	Serv instrumentation		INSA	4
14	Discharge	laser based discharge Meas.	Meas.	Ijinus	ISCO laser	INSA	9
24*	Multi	Submersible spectrometer	Meas.	Go-Sys	ISA	INSA	9
25	Multi	Colour sensors	Meas.	Elscolab	AF16/F26	INSA	7
26	Multi	SQUID	Meas.	in-house development	SQUID	EAWAG	4
27*	Multi	Non-contact quality sensor: multispectral camera	Meas.	Headwall photonics	Hyperspec MV.X	EAWAG	0
31*	PAH	PAH fluorometer	Meas.	Aquams	TriOS	INSA	9
33*	Pipe mapping	FSB	Meas.	Deltares	FSB	EAWAG	5
38	Rain	Raingauge with Corriolis flowmeter	Meas.	DIY	DIY	INSA	2
43*	Sediment	3d mapping of sediment with LiDAR camera	Meas.	Intel RealSense	LiDAR Camera L515	UDC	2
44	Sediment	Low Cost 3d mapping of sediment with SfM	Meas.	NA	DIY - Commercial photo camera	UDC	4
55	Water quality	Microsensors	Meas.	Unisense	various	UoS	9-1

[1] We defined four types of sensors and digital monitoring solutions: Meas. = measurement instrument, Control= actuator, Data transmission= logging or wireless transmission technology, Other= all other devices, e.g. energy harvesting power supply

[2] Internal estimate of the technology readiness level. This is sometime not well defined, because a sensor can also be used outside of its original scope. Examples: Using a Pt_100 thermistor to measure sediment depth based on temperature fluctuations, or a soil moisture probe as a low-cost detector of combined sewer overflows.

TABLE 8: FULL LIST OF SENSORS

ID	Parameter	Sensor title	Type[1]	Brand	Model	Proposer	TRL$_{est}$[2]
1	Acoustic Turbidity	Acoustic T and Velocity	Meas.	Ubertone	Ubflow	EAWAG	9-1
2	Acoustic Turbidity	Nivus PKM prototype	Meas.	Nivus	PKM	EAWAG	7-1
3	Acoustic Turbidity	Hydrovision Sediment monitor	Meas.	Hydrovision sensor	SediScat	EAWAG	7-1
4	Acoustic Turbidity	Acoustic T and Velocity	Meas.	Ubertone	Ublab	UDC	9
5	BOD5	Continuous DBO5	Meas.	Node		INSA	8
6	**Coliforms (faecal, E. coli, total)**	**Proteus**	**Meas.**	**Proteus**	**Multi-par. Water Quality Sensor**	**UoS**	**8**
7	**Conductivity**	**LoRaWan Conductivity**	**Meas.**	**in-house development**	**inductive EC probe**	**EAWAG**	**4**
8	Conductivity	Conductivity low-cost	Meas.	Atlas Scientific	Mini Cond K 1.0 kit	INSA	2
9	CSO event	LoRaWan CSO detector	Meas.	in-house development	capacitative sensor	EAWAG	4
10	Data Transmission	LoRaMesh Node	Data transm.	DIY	LoraMesh	Eawag	7
11	Discharge	Pneumatic flow limiter	Control	Stebatec	pneumatischer Abflussregler	INSA	9
12	**Discharge**	**Camera Flow Meter**	**Meas.**	**Photrack**	**Discharge Keeper**	**EAWAG**	**5**
13	Discharge	Coriolis flowmeter	Meas.	Serv instrumentation		INSA	4
14	discharge	laser based discharge Meas.	Meas.	Ijinus	ISCO laser	INSA	9
15	Discharge	Discharge low cost	Meas.	Atlas Scientific	3/4" flow meter kit	INSA	2
16	Dissolved oxygen	DO low cost	Meas.	Atlas Scientific	Analog DO kit	INSA	2
17	Energy	Energy harvester	Other	in-house development		EAWAG	1
18	Flow	Area Velocity sensor	Meas.	teledyne isco	TIENet™ 350	UDC	9

ID	Parameter	Sensor title	Type[1]	Brand	Model	Proposer	TRL$_{est}$[2]
19	Flow velocity	Low-cost camera for LSPIV/BIV	Meas.	DIY	picamera, raspberry	UDC	3
20	FOG and floating debris monitoring	FATracker	Meas.	-	FATracker 1	Deltares	6
21	Granulometry	On-line granulometry	Meas.	Malvern	Insitec L & SX	INSA	4
22	Infiltration	DTS for infiltration	Meas.	Sensornet	Sentinel	EAWAG	2
23	Micropollutants	MS2field	Meas.	in-house development	DIY	EAWAG	0
24	**Multi**	**Submersible spectrometer**	**Meas.**	**Go-Sys**	**ISA**	**INSA**	**9**
25	Multi	Colour sensors	Meas.	Elscolab	AF16/F26	INSA	7
26	Multi	SQUID	Meas.	in-house development	SQUID	EAWAG	4
27	**Multi**	**Non-contact quality sensor: multispectral camera**	**Meas.**	**Headwall photonics**	**Hyperspec MV.X**	**EAWAG**	**0**
28	Multi	scan conductivity probe	Meas.	s::can	condu::lyser V2	UDC	9
29	Multi	Low cost RGB-LED spectrophotometer	Meas.	DIY	prototipe	UDC	5
30	ORP	ORP low cost	Meas.	Atlas Scientific	Analog ORP kit	INSA	2
31	**PAH**	**PAH fluorometer**	**Meas.**	**Aquams**	**TriOS**	**INSA**	**9**
32	pH	pH low ost	Meas.	Atlas Scientific	Analog pH kit	INSA	2
33	**Pipe mapping**	**FSB**	**Meas.**	**Deltares**	**FSB**	**EAWAG**	**5**
34	Pump	Pump low cost	Control	Atlas Scientific	kit-PMP	INSA	2
35	Rain	Camera Rain Gauge	Meas.	waterview	weatherCAM	INSA	7
36	Rain	Laser Rain Gauge	Meas.	DIY	DIY	INSA	0
37	Rain	Microwave rain gauge	Meas.	Ericsson	Minilink	EAWAG	0
38	Rain	Raingauge with Corriolis flowmeter	Meas.	DIY	DIY	INSA	2
39	Rain	Disdrometer	Meas.	OTT	Parsivel2	UDC	9
40	Sediment	3d mapping of sediment with lidar	Meas.	DIY	DIY	INSA	2
41	Sediment	Sediment with sonar	Meas.	Marine Electronics	2512 ETH	INSA	8
42	Sediment	DTS for sediment	Meas.			EAWAG	9
43	**Sediment**	**3d mapping of sediment with LiDAR camera**	**Meas.**	**Intel RealSense**	**LiDAR Camera L515**	**UDC**	**2**

ID	Parameter	Sensor title	Type[1]	Brand	Model	Proposer	TRL$_{est}$[2]
44	Sediment	Low Cost 3d mapping of sediment with SfM	Meas.	NA	DIY - Commercial photo camera	UDC	4
45	Sediment	3d mapping of sediment with depth sensor camera	Meas.	Intel RealSense	Depth Camera D435	UDC	2
46	Sediment sampling	Use of carbonic ice to freeze sediment bedload samples	Meas.	DIY	DIY	UDC	2
47	Sediment sampling	Sediment stratification with videoscope	Meas.	Olympus	IV86-AT80S IPLEX	UDC	4
48	Sediment sampling	unaltered' sediment bedload sampling in manholes	Meas.	DIY	SedimenThor	UDC	4
49	Temperature	Temperature for gully sediments	Meas.	in-house development		EAWAG	0
50	Temperature	Temp low cost	Meas.	Atlas Scientific	PT-1000 Temp kit	INSA	2
51	TSS	TSS sensors	Meas.	Elscolab		INSA	7
52	TSS	scan TSS probe	Meas.	s::can	soli::lyser V1	UDC	9
53	Turbidity	Low-Cost Turbidity probe (dishwashing machine)	Meas.	Seeed Studio	Turbidity Sensor	UDC	0
54	Water depth	Low-cost ultrasound sensor	Meas.	DIY	JSN-SR04T	UDC	2
55	Water quality	Microsensors	Meas.	Unisense	various	UoS	9-1

[1] We defined four types of sensors and digital monitoring solutions: Meas. = measurement instrument, Control= actuator, Data transmission= logging or wireless transmission technology, Other= all other devices, e.g., ambient energy harvester for energy self-sufficient monitoring systems

[2] Internal estimate of the technology readiness level. This is sometime not well defined, because a sensor can also be used outside of its original scope. Examples: Using a Pt_100 thermistor to measure sediment depth based on temperature fluctuations, or a soil moisture probe as a low-cost detector of combined sewer overflows.

TABLE 9: COMPLEMENTARY INFORMATION FOR THE FULL LIST OF SENSORS

ID	Weblink or info
1	Ubertone
2	https://www.nivus.com/en/
3	https://d3pcsg2wjq9izr.cloudfront.net/files/25630/download/628118/HydroVision_SediScat_sediment_meter_brochure_2014.pdf
4	https://www.ubertone.com/products-ub-lab-uvp.html
5	publi_solutions_node_en.pdf (hydreka.com)
6	https://www.proteus-instruments.com/parameters/total-coliform-sensors/
7	https://www.uwo-opendata.eawag.ch/
8	https://atlas-scientific.com/mini-conductivity-k-1-0-kit/
9	https://www.eawag.ch/en/news-agenda/news-portal/news-detail/mit-dem-internet-der-dinge-die-abwasserentsorgung-verbessern/
10	https://doi.org/10.1109/ACCESS.2019.2913985
11	Pneumatic discharge control partially filled TF-PNA | STEBATEC
12	DischargeKeeper (photrack.ch)
13	http://www.servinstrumentation.fr/produits/massique-coriolis-micromotion.php
14	https://www.ijinus.com/produit/par-metiers/environnement/debitmetre-isco-laserflow/#tab-description_tab
15	https://atlas-scientific.com/3-4-flow-meter-kit/
16	https://atlas-scientific.com/gravity-analog-do-kit/
17	https://arxiv.org/abs/2204.03748
18	NA
19	https://projects.raspberrypi.org/en/projects/getting-started-with-picamera
20	https://www.youtube.com/watch?v=R_G7hVlTje8
21	https://www.malvernpanalytical.com/fr/products/product-range/insitec-range/insitec-wet
22	NA
23	NA
24	UV/VIS - Spectrometers (go-sys.de)
25	Optek_C4000-C8000_Convertisseurs-Photometriques-Universels_1.pdf (elscolab.com)
26	NA
27	https://www.ehd.de/products/announcements/EHD-SCM2020-UV-TR-Camera.html
28	https://www.qsenz.nl/application/files/1814/5502/5642/condulyser-manual-V2-20101126.pdf
29	https://doi.org/10.3390/s20195631
30	https://atlas-scientific.com/gravity-analog-orp-kit/
31	https://www.aquams.com/mesure-en-continu/sonde-hap-hydrocarbures/
32	https://atlas-scientific.com/gravity-analog-ph-kit/
33	NA
34	https://atlas-scientific.com/ezo-pmp-kit/
35	https://www.waterview.ai/
36	NA
37	NA
38	NA
39	https://www.ott.com/es-la/productos/meteorologia-80/ott-parsivel2-272/

40	NA
41	Marine Electronics Ltd. - Mini Pipe Profiling Sonar - 2512 Ethernet (marine-electronics.co.uk)
42	NA
43	Intel RealSense LiDAR Camera L515
44	NA
45	Intel RealSense Depth Camera D435
46	NA
47	Olympus Videoscope IPLEX G Lite
48	NA
49	NA
50	https://atlas-scientific.com/pt-1000-temperature-kit/
51	Optek_C4000-C8000_Convertisseurs-Photometriques-Universels_1.pdf (elscolab.com)
52	https://www.qsenz.nl/application/files/7714/5502/5858/solilyser-manual-V1-20091124.pdf
53	https://www.mouser.es/ProductDetail/Seeed-Studio/101020752?qs=GBLSl2AkirtzYUD8apNtDw==&mgh=1&vip=1&gclid=Cj0KCQjw7MGJBhD-ARIsAMZ0eetRnX3KvpnZ0L04kLAzE0S3q7plHHwX6HmrU9g5LGq1DCq-R6jVzHYaAuesEALw_wcB
54	https://amzn.to/2XdsHeH
55	https://unisense.com/product-category/sensors-electrodes/