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Chapter 11

Data collection in urban drainage and stormwater management systems – case studies

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ABSTRACT

Data collection in urban drainage systems comes with many challenges. However, many examples already exist, containing numerous useful lessons learned. This chapter therefore contains several urban drainage and stormwater management metrology case studies, selected to cover a wide range of scopes, scales, objectives, climates, data validation methods, and data storage approaches. The case studies are initiated by academics as well as by institutions from the water industry.

Keywords: Costs, data collection, organization, lessons learned, project planning.

11.1 INTRODUCTION

Challenges in urban drainage monitoring are numerous. Many types of monitoring devices are deployed in urban drainage and stormwater management (UDSM) systems, and there are different ways of designing, maintaining and operating monitoring networks. People in different types of organizations may pursue various approaches to validate, store and manage their data collected in the field. This chapter describes a handful of diverse case studies to serve as illustrations of common challenges as well as lessons learned when implementing urban drainage metrology projects. These case studies were selected to cover a wider range of different types of metrology projects: from different countries, climates, monitoring objectives – from research-driven to full-scale applications in practice – organizational arrangements and local guidelines. Each monitoring initiative seems unique – all come with their own challenges and opportunities.

The following case studies are described and their links to the most relevant chapters are detailed in Table 11.1.

- **Real-time control for improvement of receiving water quality, Eindhoven, The Netherlands.** This is an example of a long-term urban drainage monitoring initiative, started in 2006 and still ongoing in 2020, including rain gauges, flow gauges and quality monitoring in sewer networks and an urban river. An example of a collaboration between three parties for the installation and management of sensors (a waterboard, a municipality and a consultant), where the technical questions of the consultant (can I do RTC – real time control?) also led to successful research within universities.

Table 11.1 Case studies and main related chapters.

Case study/chapter	1	2	3	4	5	6	7	8	9	10
Eindhoven		X	X		X	X			X	X
SMART		X				X	X	X	X	
The Basin			X				X		X	
Anglian Water		X	X		X	X	X		X	
Impakt			X							
Nextgen		X	X	X	X	X	X			
UWO		X	X		X	X	X		X	X

- **Let's SMARTly combat flood in Kuala Lumpur, Malaysia** describes the operation of the SMART Tunnel, which has a dual function of accommodating road traffic as well as flood diversion. This illustrates real-time decision-making based on rainfall, urban river depth and CCTV (closed circuit television) monitoring. The tunnel has been operational since 2007.
- **Wicks Reserve bioretention basin, The Basin, Victoria, Australia** describes monitoring of shallow groundwater and flows into a bioretention basin. This illustrates tipping bucket rain gauge monitoring, challenges that come with monitoring shallow flows in stormwater facilities and fully capturing hydrograph tails.
- **Flow monitoring campaign for company-wide integrated urban drainage model upgrade, Anglian Water Services, United Kingdom.** This illustrates the systemic application of industry standard flow monitoring guidelines and model verification guidelines in the United Kingdom. It covers the approach of a UK private water company for the upgrade and maintenance of sewer network models, with 3500 flow monitors and 800 rain gauges installed by subcontractors for shorter periods over two years in different catchments. It includes rainfall monitoring using rain gauges and radar, as well as sewer system flow monitoring. It describes its own machine learning tool for quality checking of flow data and tips for placing flow monitors and health and safety considerations.
- **'Impakt' – Optimization of the urban drainage systems in the Dommel and Warmbeek river subbasins, from a river quality point of view, Flanders, Belgium**. This case study describes rainfall and flow monitoring in sewer systems to obtain a sound understanding of system hydraulics and eventually inform integrated water quality models for scenario testing. A mixture of short- and long-term flow surveys, managed by sub-contractors and an in-house team, with long-term campaigns to capture seasonal patterns and identify dry weather flow variations. A clear meta-data and data legacy strategy is described, with helpful tips for sensor locations and lessons learned.
- **'NextGen' Urban Water Monitoring – A highly distributed field monitoring of an urban drainage network with affordable sensors and real-time data communication, Australia.** This is an example of low-cost telemetered water depth sensors, EC (electrical conductivity) sensors, and rainfall monitors using Arduino technology. The sensors are aimed at being easy to install, and low cost, and thereby achieving very high-resolution data. The raw data are publicly accessible via a website.
- **The UWO – A field laboratory for distributed real-time monitoring with low-power sensor and data communication technology, Fehraltorf, Switzerland.** This case study describes a long-term initiative to monitor the urban water balance using low-power sensors and low-power wide area networks (LPWAN) technology. It combines traditional monitoring techniques with Internet of Things (IoT)-driven approaches. It provides lessons learnt from a practical point of view regarding data communication issues, large-scale sensor management, design of networks and data validation. Validated data is publicly accessible through a data dashboard.

In the remainder of this chapter occasionally the costs of materials and/or installations are mentioned in a variety of currencies, these are converted to amounts in Euro. However, as it is not exactly known which price level was used in the original amounts, the conversion to Euro is based on the average exchange rate over 2019, therefore the figures mentioned are to be regarded as an indication only and are *certainly not meant* to be used as a basis for budget estimations.

Key messages from urban drainage metrology case studies

- KM 11.1: *Challenge* – Keeping urban drainage and stormwater management metrology projects going long term is very challenging.
- KM 11.2: *Harmonization* – Existing urban drainage metrology projects tend to have bespoke data quality management and data/meta-data storage systems. The quest to achieve a more harmonized approach to data quality management and data storage remains open, with questions as to what level of harmonization would be desirable, and what such an approach should look like.
- KM 11.3: *Maintenance efforts* – The person-costs for management and maintenance of both sensors and databases should not be underestimated. These usually exceed the costs of the actual sensors by far and are ongoing throughout the project. Successful metrology projects foresee sufficient budget for operation and an efficient maintenance strategy.
- KM 11.4: *Guidelines* – A range of practical urban flow monitoring guidelines exists. Some countries have nationwide recognized practitioner guidelines, whereas in other countries this information is held within individual drainage authorities or companies. Practitioners will have to adhere to such guidelines, whereas academic researchers would need to know *what* these guidelines are *when* setting out on a collaborative metrology project. Researchers would need to first work within these guidelines before they are able to compare existing and new methods, and gather evidence, that other methods may work better. Without going through this step, new methods are very unlikely to be widely adopted.
- KM 11.5: *Water utility planning cycles* – Researchers should bear in mind water utilities planning and management cycles. This can help to find the optimal time to set up new metrology projects, as well as identify and prepare for continuity issues in longer-term projects.
- KM 11.6: *Low-power and low-cost* – There are emerging opportunities for distributed extensive urban drainage and stormwater management metrology deploying lower cost sensors. This is attractive for researchers, utilities, and authorities to gain a bigger picture by wider monitoring of infrastructure and capturing a more complete range of events. Data quality checking and data management become even more crucial when working with such a technology at larger scales, whereas the design of monitoring networks includes redundancy of sensors and assumes relatively short lifespans of sensors.

11.2 REAL-TIME CONTROL FOR IMPROVEMENT OF RECEIVING WATER QUALITY, EINDHOVEN, THE NETHERLANDS

11.2.1 Scope and objectives

11.2.1.1 Scope

The Dutch Waterboard 'Waterschap de Dommel' (WDD) operates a large-scale monitoring network with 83 sensors in the sewage transport network of Eindhoven, The Netherlands and in 181 adjacent, cooperating municipalities (as of June 2019). The monitoring initiative was commissioned in 2006 and is still ongoing. The initiating moment has been the European Water Framework Directive (WFD) (OJEU, 2000) targets set for the River Dommel, and the need to identify the most cost-effective measures to reach these targets (Langeveld *et al.*, 2013).

11.2.1.2 Objectives

The main objective of this campaign was to collect data to calibrate a set of detailed sub-models of a drainage system, WWTP (wastewater treatment plant), and river. Subsequently, sub-models were in parts simplified and combined into an integrated model, in order to study potential impacts of sewer real time control (RTC) strategies on receiving water quality. The data are also utilized to steer the rule-based RTC system, whereby the control stations and pumping stations manage the flow to a predefined amount, given the height measured before the station. More information about this case study and its RTC system is given by Schilperoort (2011), Langeveld *et al*. (2013) and van Daal-Rombouts *et al*. (2017a).

Initial findings concluded that the receiving water quality was expected to improve significantly through receiving water impact-based RTC. However, the application of this RTC scheme did not lead to full compliance with WFD requirements. van Daal-Rombouts *et al*. (2017b) described the problems that arise when trying to demonstrate how well an RTC system performs, based only on relatively short duration datasets. Hence, this project is still ongoing, with further improvements to the RTC strategy, as well as its robustness, currently being tested. Moreno-Rodenas *et al.* (2017) and Camacho-Suarez *et al*. (2019) describe research on checking uncertainty in the models used and the impact of spatial and temporal variability of input data and models used to describe the system.

11.2.2 Measured variables and location of monitors

The monitoring locations coincide with existing pumping stations and flow control stations, the latter also known as vital sewerage infrastructure (VSI). VSIs are regulated based on upstream head, with level sensors installed upstream, and the flow downstream is monitored. Rain gauges were initially installed very close to VSIs. Additional level sensors have been placed at prominent CSOs (combined sewer overflows) in the system. An overview of the number of sensors and their installation dates is given in Figure 11.1 and Table 11.2.

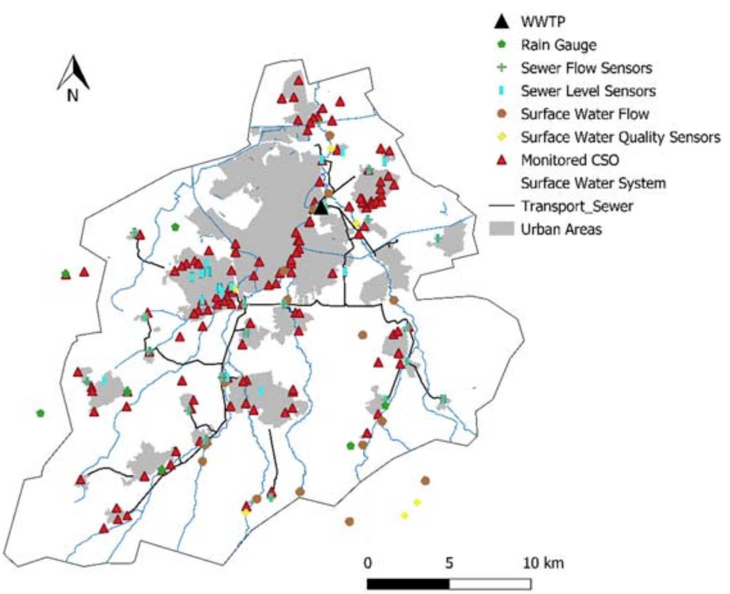

Figure 11.1 Monitoring network for Dommel River and Eindhoven urban drainage system. *Source*: Job van der Werf (TU Delft).

Table 11.2 Monitoring network in Dommel River and Eindhoven urban drainage system.

Type of measurement	Availability (from–to)	Monitoring frequency	Remarks
Precipitation	1951–now	1/h	Rainfall measurement of the Royal Netherlands Meteorological Institute
	2006–2009	1/5 min	25 rain gauges of Waterboard de Dommel
	2010–now	1/5 min	8 rain gauges of Waterboard de Dommel and Municipality Eindhoven combined with rain radar
Water level	2006–now	1/min	Water level sensors in all pumping stations and control structures (Figure 11.1) Water level sensors at 26 CSOs of Municipality Eindhoven
	2010–now	1/min	Water level sensors at all 200 CSOs
Flow	2006–now	1/min	Flow monitoring at all pumping stations, control structures and Dommel River
	2006–2009	1/min	Flow sensors at connections of municipal sewers to transport/interceptor sewer

Source: adapted from Langeveld *et al*. (2013).

11.2.2.1 Rainfall

The Royal Dutch Meteorological Institute (KNMI) operates several rain gauges (Hellman 200 cm^2, 0.1 mm resolution) within the catchment. WDD installed 25 tipping-bucket rain gauges (TBR, 0.1–0.15 mm resolution by Observator Instruments OMC-201-2 Rain Gauge) to increase the spatial distribution of rainfall information. However, the data quality of *some* WDD TBRs was too poor to be useful. Rain gauge installations had been realized very close to tree cover or large infrastructures (Schilperoort, 2011), leading to largely deviating rain depths that could not attributed to spatial rainfall variability. Hence, some of these locations were abandoned, and since 2009 eight rain gauges have been operated by WDD in the area. Merging nationwide C-band radar rainfall estimation (5 min aggregated at 1 km^2 resolution) with rain gauge data, and the effect of rainfall resolution on integrated water quality model simulations have recently been investigated and described in Moreno-Rodenas *et al*. (2017).

11.2.2.2 Flow

Flow control stations in this context refer to stations with a bypass. When a certain threshold is reached, a moveable weir shuts the main pipe and redirects the flow through a smaller pipe, causing filling of the pipes upstream. An electromagnetic flowmeter is connected to the bypass, only showing readings while the main pipe is shutoff.

'Gemaal Aalst' is the main pumping infrastructure in the RZ transport system (RZ is an acronym for 'Riool Zuid'; the southern main branch of the transport system), with a maximum flow of 12,000 m^3/h through two pressure mains. Pressure mains and pumping stations are monitored using electromagnetic flow monitors.

In pumping stations different types of submersible pressure transmitter are used for measuring flow depth. Rather than submersible pressure sensors, an ultra-sonic option was adopted for the CSOs due to them not being constantly submerged. Some newer measuring points, where municipalities connect into the main transport lines, are now equipped with radar sensors.

11.2.3 Sensor operation and maintenance

The sensors are validated (see Chapters 7 and 9) within the Delft-FEWS (Flood Early Warning System) WIS (Water Information System) platform (Deltares, https://oss.deltares.nl/web/delft-fews, accessed 17 June 2021). This platform is mainly used as a central database, in order to assess if a particular sensor needs recalibration or other calamities are occurring with the sensor. If this is the case, the maintenance team can assess the situation on site. Cleaning maintenance is done regularly; the frequency of cleaning depends on the type of sensor, location and importance. Rain gauges are cleaned and recalibrated yearly, whereas oxygen sensors in the surface water are checked twice a month.

Service levels are given to sensors that are maintained by third-party service providers. They detail the maximum response time to calamities with the sensor and the need for cleaning maintenance. Continuity of the monitoring at sites allows for the analysis of trends. This was not necessarily recognized in the earlier monitoring plans, where often a rotary scheme was adopted to cover more ground with less investment cost. These campaigns have been useful for short term analysis and understanding of the system, but for research purposes often did not yield enough information.

Sensor power management does not pose significant problems for the main measuring points near VSI. However, other measuring points need to be either battery powered or have a separate power set-up constructed near to them. This is also an imperative when choosing the location for the sensors. Battery replacement is a key task of the maintenance team, batteries are changed approximately yearly for all the data loggers, or sooner in the case where investigation of a communication black-out has shown a need for replacement.

11.2.4 Data management and data accessibility

All the sewer-related data from WDD are currently logged within a *GE Historian* database (https://www.ge.com/digital/applications/proficy-historian, accessed 17 June 2021). This is connected to the central SCADA (supervisory control and data acquisition) at the WWTP, where all real-time information is used for the operation of the system. On a daily basis (at 6 a.m.), the data are read into the *FEWS Water Information System (WIS)* system. WIS is similar to GIS (Geographic Information System) for water related data. It follows the same principles for more instinctive representation of data. *GE Historian* does not have an easy GIS interface and is used as a background storage place for the data, where the FEWS allows interaction.

Front-ends: There are various platforms, through which the data can be retrieved. The main forms of data collection (when larger datasets are required) are through Microsoft Excel® (through the Proficy Historian Add-on) or Matlab. These forms require knowledge of the 'tagnames', which are scattered throughout the WDD systems. The data can also be approached through Z-Info and a FEWS WIS system. The FEWS WIS system is a GIS-based system which calls the data from *GE Historian*, allowing the user to find the relevant tags (and data, if desired) for known locations. It also instantly visualizes the requested data.

Two others external 'data-tools' are in use by WDD: TMX and HydroNET. TMX (http://www.tmx.nl, accessed 28 April 2021) is a larger, system-wide framework for both soft- and hardware. The TMX system is used for surface water quality readings, but the sewer related data points are also read into the TMX environment. HydroNET (https://www.hydronet.com/, accessed 28 April 2021) uses the databases for operational use and is not linked to research.

11.2.5 Data validation

There are set requirements to the quality and availability of data set by WDD. These depend on the location, information need/use of information and type. WDD requires that (i) raingauges have a 0.1 mm resolution and (ii) 95% confidence intervals for measured water levels are 24 mm wide. Other accuracies are reported as % rather than absolute values. The availability of data for the *Kallisto* project (Langeveld *et al.*, 2013), and later adopted throughout WDD, was 90%, meaning that the sensors should operate successfully 90% of the time. In the past, these requirements have not been met due to shortage of dedicated staff time (reports suggesting 50% for particular sites) but are likely to be more obtainable as monitoring of the system becomes a more integral part of the WDD duties.

All new sensors will be placed using internal protocols, as specified by the manufacturer. To ensure the correct operation, two tests are performed: a Factory Acceptance Test (FAT) to check if the sensor functions according to the factory specification and a Site Acceptance Test (SAT) which involves checks for time-synchronization with the atomic clock and sensor calibration according to internal protocols and depending on sensor types. The SAT is repeated after a sensor has been installed for some time and is expected to have drifted.

There are two streams of data available in all platforms: raw data (RD) and processed data (PD). *GE Historian* only stores raw data, with validation starting at the *FEWS* level. The validated data are then available in parallel to the raw data, which enables researchers to re-validate raw data based on the specific requirements for their project.

Primary validation is completely automated, looking if the values are within certain limits: range check (min/max) and noisiness (see Section 9.3). This validation is based on the local parameters and therefore both site specific (local minima and maxima) and factory specific (noisiness). Secondary validation is non-automated or semi-automated (see Section 9.5). This process can override whatever decisions are made by the automation in the first step. It is highly site specific and based on the knowledge of the system. This also includes cross-comparison of different related parameters within the system, such as the rainfall with hydrodynamic responses of the system (van Bijnen & Korving, 2008). Further details of the data-yield of the monitoring network, which was poor at the start of the project for various reasons, are described in Schilperoort (2011).

There are several performance indicators (PIs) in use to improve the monitoring system. These are based on interviews with different departments in the WDD, to ensure PIs are aligned with what is required. The PIs used are data availability, fraction usable data, and accessibility.

Data availability refers to the fraction of data points that arrive in the database (dependent on quality of data transmission). The fraction usable data is the part of the arrived data that passes the validation stages (quality of the sensors), and accessibility is the ability for the data to be used effectively and rapidly (therefore dependent on the database and data communication structure).

There is a high variability in the quality of the data stream, for both data availability and fraction usable data. Over the 2007–2008 period, the average data availability per sensor cluster ranged from 70–99%, with the fraction usable data ranging from 0–99%. In general, sensors installed in the WWTP influent pump performed well, whereas UV/Vis sensors performed most poorly.

11.2.6 Data transfer and communication system

Depending on the purpose of the measurement, the dataflow goes through different communication platforms. If there is a need for a bidirectional communication because of a control measure, the communication needs are different. The communication from the SCADA to the actuators in the system is through TCP/IP (transmission control protocol/internet protocol). Given that these are large buildings, TCP/IP or Ethernet is viable, as opposed to more remote monitoring locations. For monitoring purposes only, GPRS is sufficient for data transmission. Vodafone and/or T-mobile SIM cards are in place to allow for the GPRS connection. When two are in place, the logging can continue during calamities with the parallel SIM card.

11.2.7 Reporting, management and availability of data files for research

Within WDD, five-year cycles are defined, where monitoring targets are defined, including parameters, monitoring frequency, confidence intervals (% or absolute value) and availability (operational % of the time).

This cycle 'starts' by creating a monitoring cycle plan (MCP), which sets out how the monitoring should be carried out both financially and operationally, and determines the requirements for information. Based on this plan (expansion of) the monitoring network is set up and maintenance plans are drawn up. Based on the new (maintained) monitoring networks, data are harvested, validated, and ultimately used for analysis of the system. These analyses are reported along with whatever actions deemed necessary by the operator. Based on this, new information might be required, which is then set out in the new monitoring cycle plan (Sections 6.1 and 6.2).

The MCP is an integrated report and requires input from several departments within WDD (as it pertains to surface water (hydrobiology, hydrodynamics, etc.), sewerage (quality and quantity of flow) and groundwater (hydrogeology). This integrated approach to the MCP allows for 'optimized' data flow.

11.2.8 Challenges, lessons learnt

Monitoring is not always seen as a priority by WDD management, which is elected for 4 years, and monitoring is likely to become more fruitful over a longer time horizon. This is a potential hurdle, which needs to be overcome for other Waterboards. For the entire WDD governed area (e.g. not just Eindhoven urban drainage area), the cost for maintaining and operating the monitoring network is roughly € 2.5 million annually (on an overall total annual budget of € 110 million).

A key suggestion for improvement, based on the opinions of researchers working on ongoing collaborative research projects with WDD, would be to include meta-data (type of sensor, calibration results and maintenance issues) within the FEWS system, rather than have it scattered in disjointed Microsoft Excel® files (Section 5.3). This way, the FEWS database takes in all the necessary data, with reporting on data and ease of analysis expected to improve significantly.

The use of several platforms has led to a lacuna of knowledge, causing a lack of ability to use the entire range of options within each different platform. With the external tools (HydroNET and TMX mainly), the knowledge tends to reside outside WDD, which can lead to trouble for the maintenance or changes in the system. Although the current logging of the data is adequate for all purposes (both retrieval of past datasets and operation), data from before the change to the current database architecture seems to have been lost. Before the use of the *GE Historian* database, a database from another company (GBS) was used. Theoretically, the data within this database should still be there. However, despite numerous efforts from various operators and other relevant WDD employees, these data points have not yet been recovered. *Transitioning to new databases should therefore at all times consider future needs for data and ensure the availability of past data is preserved.*

A collaboration between several organizations (a waterboard, several municipalities, at least four consultants, several manufacturers and construction firms, and a university) whereby especially the waterboard, the municipalities and the university have different requirements regarding data quality and different aims in mind, needs careful project management that is considerate of these different viewpoints. Achieving high data quality is often not seen as financially viable or desirable by practitioners, hence collaboration and input of PhD students proved essential to achieve good data validation in this case study. The amount of work needed to maintain a monitoring network of this scale was initially underestimated, with 0.5 FTE (full time equivalent) available for all tasks during the first year. This resulted in, euphemistically formulated, a less than optimal installation of rain gauges and a lack of sensor maintenance and numerous changes in the set-up during the first years of the project.

11.3 LET'S SMARTLY COMBAT FLOOD IN KUALA LUMPUR, MALAYSIA

11.3.1 Scope and objectives

The Stormwater Management and Road Tunnel, famously known as SMART Tunnel, is an innovative approach to mitigate flooding in the heart of Kuala Lumpur City Centre. The capital of Malaysia experiences frequent flood events, the first recorded event was in 1881 (Williamson, 2015), due to the high intensity of precipitation within a short duration. The booming development of Kuala Lumpur saw changes in the land types, decreasing infiltration capacity, increasing high surface runoff and subsequently more frequent flood events. The intensity of a rainfall episode in Kuala Lumpur can be as high as 120 mm/h (Abdullah *et al.*, 2019), which results in high volume discharge into the river as well as immediately exceeding the urban drainage capacity. SMART Tunnel serves not only as the solution to flooding but also provides an alternative route to reduce traffic congestion both inbound and outbound of Kuala Lumpur.

The Department of Irrigation and Drainage (DID) operates the facility, which came into operation on 30th June 2007 after almost four years of construction worth close to RM 1.93×10^9 (i.e. 1.93 billion) (being equivalent to ~€ 0.39 billion). The main objective of this mega structure is to divert high flow discharge at the critical confluence of the Klang and Ampang Rivers. The design aims to reduce or minimize the probability of inundation at the downstream confluence of the Klang and Gombak Rivers,

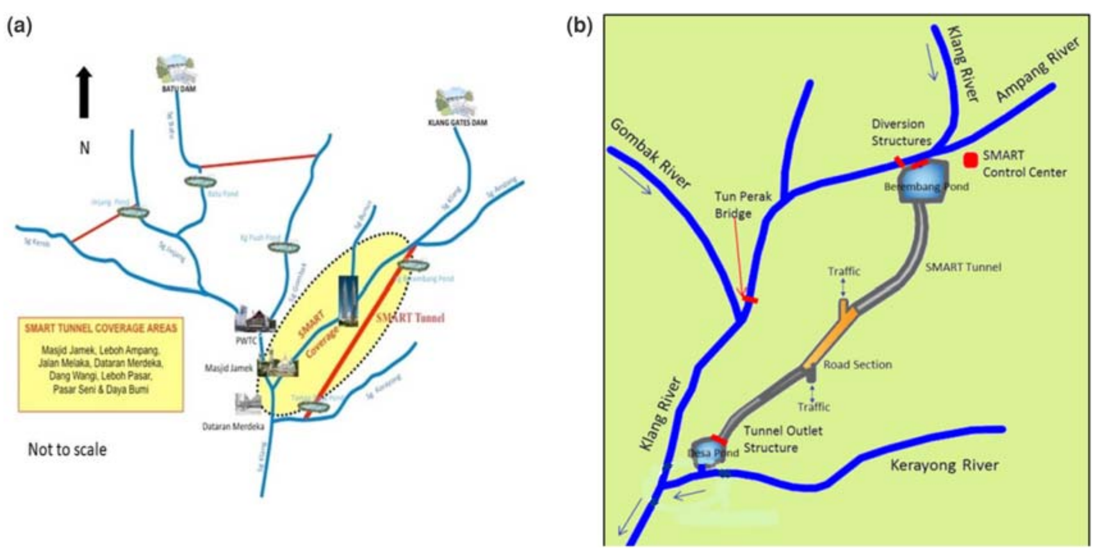

Figure 11.2 The location of SMART Tunnel alignment (a), diverting the discharge from Klang/Ampang Rivers to Kerayong River (b), minimizing flood occurrence within the marked SMART coverage. *Source*: Department of Irrigation and Drainage, Malaysia.

where the Masjid Jamek is (as shown in Figure 11.2(a)). The design consideration is that the peak flow here should not exceed 180 m^3/s (Lai, 2016). At this point, the discharge is from an approximately 160 km^2 watershed of the upper Klang River catchment. The SMART was designed to cater to a 100-year average recurrence interval (ARI) flood event with a maximum diversion volume of 300 m^3/s.

Shown in Figure 11.2(b), the flow from the upper catchment of the Klang and Ampang Rivers is diverted to the Berembang holding pond before flowing through the 9.7 km bypass, 13 m diameter tunnel into the Desa attenuation reservoir located at the downstream of the Kerayong River.

11.3.2 Operation of SMART

The facility operates in four modes, as illustrated in Figure 11.3 depending on the flow discharge from the Klang River. Figure 11.4 indicates the frequency with which the different operational modes for SMART have occurred from 2007 to July 2020.

11.3.2.1 Mode 1

Activated when the weather is fair with little or no rain and the traffic is allowed in the tunnel.

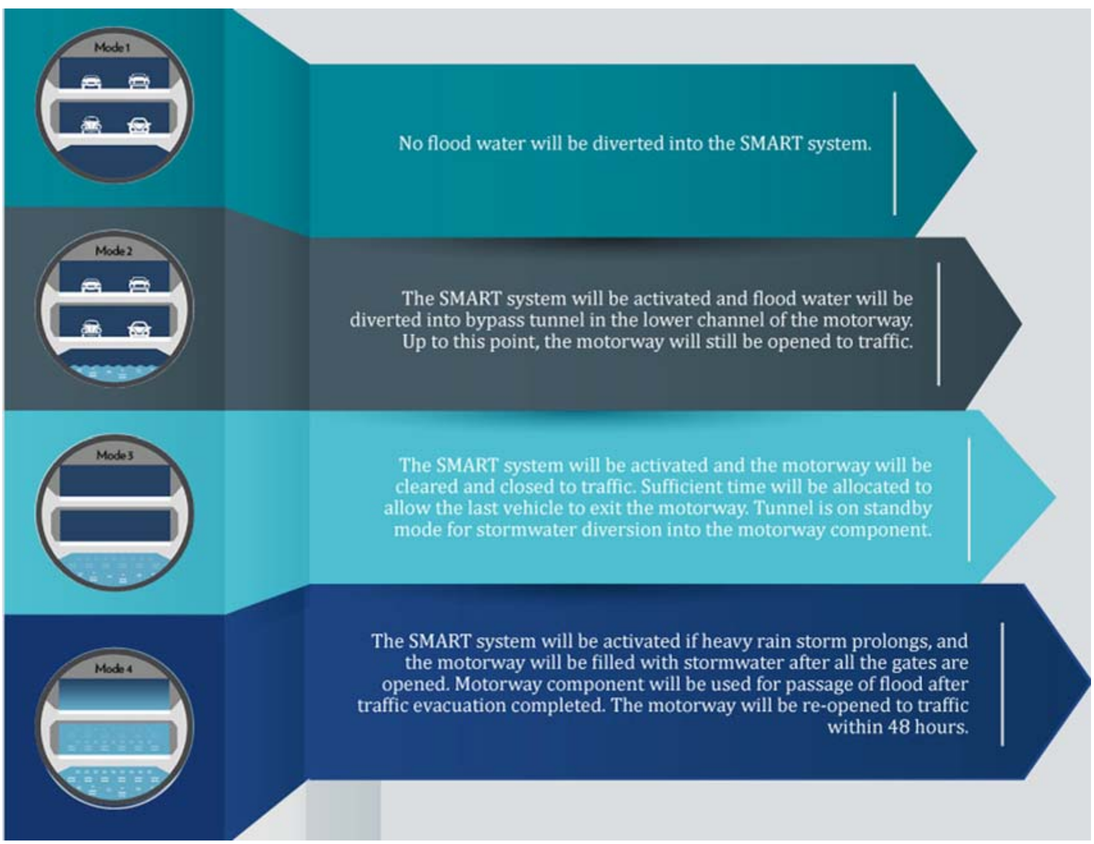

Figure 11.3 Four modes of SMART operation. *Source*: Department of Irrigation and Drainage, Malaysia.

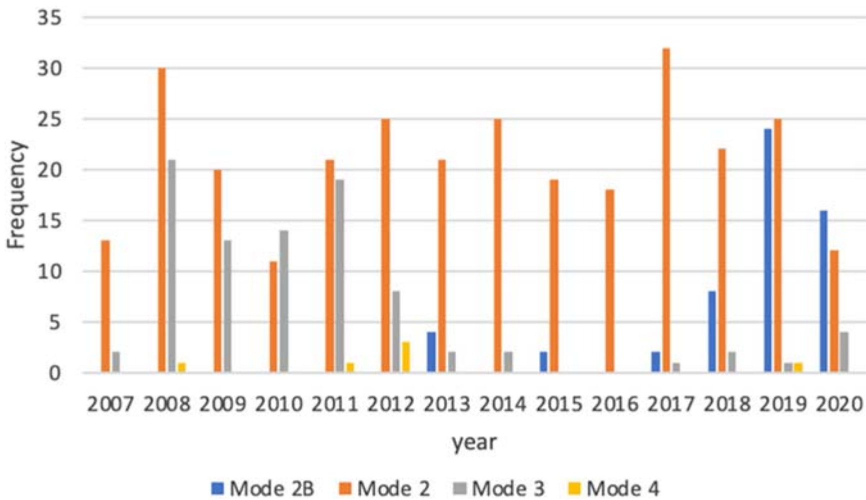

Figure 11.4 Frequency of operational modes for SMART from 2007 to July 2020. *Source*: Department of Irrigation and Drainage, Malaysia.

11.3.2.2 Mode 2

Mode 2a: Activated when a moderate rainfall event occurs and the flow rate recorded at the confluence of the upper Klang River/Ampang River is 30 m^3/s. In this mode, all the discharge will be diverted into the holding pond. This mode will be activated when there is heavy rainfall in the city centre and downstream of the confluence of the upper Klang River/Ampang River.

Mode 2b: Activated when a moderate rainfall event occurs and the flow rate recorded at the confluence of the upper Klang River/Ampang River is 70–150 m^3/s. In this mode, only 50 m^3/s is allowed to flow downstream of the Klang River, and the rest of the discharge will be diverted into the tunnel. Based on the records, normally Mode 2 is activated for rainfall events with less than 10 year ARI and depends on the rainfall duration.

Excess flood water will be diverted to the Berembang Pond. Mode 2 allows only the lower drains of the tunnel to be used conveying the flow to the Desa attenuation pond.

The road tunnel will still be opened to traffic.

11.3.2.3 Mode 3

Activated when a major storm event occurs and the flood model forecasts a flow rate of 150 m^3/s or more (but not exceeding the designed Q_{100} of 300 m^3/s) at the confluence of the upper Klang River/Ampang River during this particular storm event. The flood detection system (FDS) predicts the flow (and water level) at the city centre (i.e. Tun Perak Bridge) based on the rainfall data within the catchment.

Traffic will be evacuated from the road tunnel, which normally takes about one hour. In this mode, only 10 m^3/s is allowed to flow downstream of the Klang River to provide storage for the high incoming flow at the downstream. The rest of the discharge will be diverted to the tunnel.

If the heavy rainstorm within the Klang River catchment stops early or due to some specific circumstances, then the traffic tunnel is expected not to be flooded and affected by the inundation.

The road tunnel will be re-opened to traffic within one to three hours after closure.

11.3.2.4 Mode 4

Activated if a heavy rainstorm is prolonged, usually will be confirmed 1–2 hours after Mode 3 is declared. Results from the FDS determine the extent of the flood.

The road tunnel will be used for passage of flood after traffic evacuation has been completed. Due to the high discharge, only 10 m^3/s is allowed to flow downstream of the Klang River and the rest of the flow will be diverted to the tunnel.

The road tunnel will be re-opened within four days of closure.

Following deactivation of SMART operations, the excess water will be pumped to the Taman Desa attenuation pond as a dewatering process.

The frequency of SMART operational modes from the year 2007 to 2020 is shown in Figure 11.4. A total of 445 SMART activated events were recorded with Mode 2 being the most common. The worst-case scenario of Mode 4 only occurred in the years 2008, 2011, 2012 and 2019. The visible trend of high-frequency Mode 3 was regularly observed for the years 2008–2011 and started to diminish from the year 2012, maintaining a lower frequency until 2020.

11.3.3 Location of monitors and measured variables

As detecting flood (through rainfall prediction) and monitoring flow (to avoid flood) are the main focuses of this facility, SMART employs a rigorous monitoring system of rainfall gauges, and water level and river velocity measurement. There are 22 rainfall stations dedicated to the SMART facility distributed within the Klang River catchment, the distance between each station is less than 3 km. The rainfall data are measured using tipping bucket rain gauges at an interval time of 5 minutes. The control centre monitors real-time data of rainfall and water level, assisting in making the decision of when to activate the SMART facility. All measured information is transferred every 5 minutes to the centralized supervisory control and data acquisition (SCADA) by transmitting the telemetry data. To ensure safety in the data transfer and storage, the communication of data to the SCADA is backed up by the GSM (global system for mobile communication) system when the radio system fails. Due to excessive data size, the data are not stored in the SIM card.

A total of 16 compact bubbler sensors are installed at strategic locations within the catchment to measure water level. A bubbler system is employed as it is more robust, especially for rivers carrying large amounts of debris such as the Klang and Ampang Rivers, in particular during high flows. The velocity of 16 strategic locations within the Klang River stretch and its tributaries is measured using Doppler current meters (DCMs). The river discharge is calculated based on the developed rating curve and validated with the record (of autocorrected discharge) from the DCM. Strategic and crucial measuring locations include the confluence of the upper Klang River/Ampang River, the SMART Control Centre (at Berembang Pond), and downstream of SMART at Kerayong River. The measurements for both river flow velocity and the water level are taken at 5-minute intervals, and data are transmitted via the same system as rainfall, through SCADA and GSM.

All instruments are powered using a solar panel with a battery pack as a supporting energy plan. In addition to advocating green technology, the solar panel also minimizes dependence on the battery simultaneously reducing operation and maintenance costs. The calculation of power consumption for a solar system for rainfall and water level stations is described in the Hydrological Procedure 32 and 33, respectively (DID, 2018a, 2018b).

Twenty CCTVs are installed at strategic locations (Figure 11.5) to provide real-time observations of water level. The critical confluence of the Klang River and Gombak River (where the popular tourist hotspot of Jamek Mosque is located) has three monitoring CCTVs. The other CCTVs are installed at the

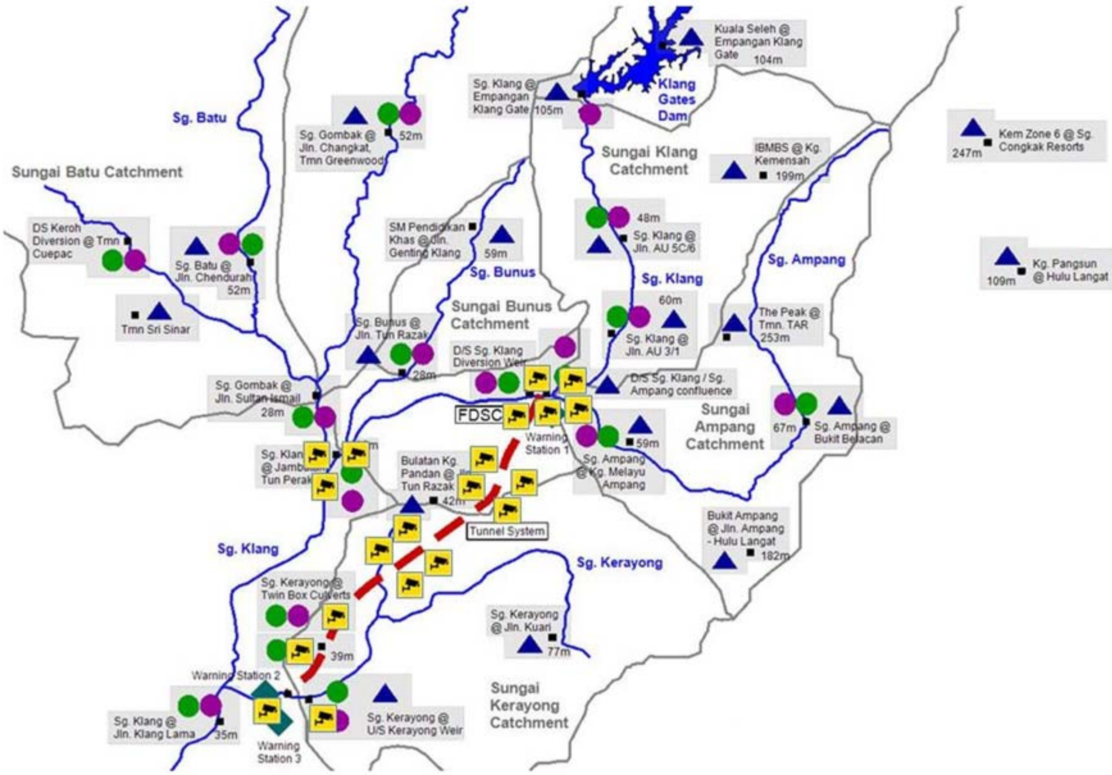

Figure 11.5 Location of the CCTVs installed within the vicinity of SMART. FDSCC – Flood Detection System Control Centre. *Source*: Department of Irrigation and Drainage, Malaysia.

SMART Control Centre, Berembang Pond, along the stretch of the Klang and Ampang Rivers and the downstream Desa attenuation pond at Kerayong River. The installation of these CCTVs is used as observed verification of the SCADA data for operational decisions.

Utilizing the fine temporal scale of rainfall data, a sophisticated and modern flood detection system (FDS) provides real-time flood forecasting information. This enables efficient and safe management of the operation of the tunnel.

11.3.4 Data management and data accessibility

All transferred raw data are stored in the SCADA database according to each measuring station, listed based on parameters and the recorded date. All recorded data are stored at the SMART data centre, internally managed by the DID. Retrieval of data is obtained using the ClearSCADA SCX MySQL relational database management system (RDBMS), allowing quick response and specific data requirements. Where the data need to be processed (usually for operational purposes), specific data will be retrieved and analysed elsewhere. In-house data quality analysis is done at the SMART Control Centre. Data availability is checked by a network connectivity test between the SCADA database and remote telemetry unit (RTU) at sites. The quality of the data is tested using hydrological modelling, by comparing the observed record with modelling results. Although at the moment (i.e. 2020), the data are only accessible to DID, upon receiving permission from DID, the data are allowed to be distributed to the interested parties. DID acknowledges that with updated technology, highly accurate algorithms and mathematical modelling, data sharing is the way forward to ensure sustainable operation of SMART. Climate-change induced rainfall patterns obviously may alter the local rainfall intensity, and subsequently the runoff volume within the Klang River watershed. By sharing the data with others, more rigorous data analysis is feasible, which provides benefits to SMART operations and the DID. Realizing the importance of data availability, all recorded data are kept in the storage server (with no data discarded after a number of years), allowing a comprehensive data review when needed.

Data obtained from the measuring gauges are of high quality, with more than 95% accuracy and minimum missing data. Even so, if there is any requirement for obvious missing data (during the transmission), data may be retrieved from the data logger on-site which has a one-month storage capacity. SMART puts heavy emphasis on flood detection and control, whereby particular attention will be paid to missing data during storm events. Accuracy checking through regular calibration procedures for the measuring equipment is done in-house, in accordance with the manual provided by the manufacturer. Well-calibrated equipment is the top priority is for operational purposes and preventive maintenance. Given the huge amount of available data, SMART engages in cleaning up the data for important and specific tasks such as analysis, prediction of storm events, and operations during high flows.

As high accuracy data are imperative, a quick response for repairing a faulty rain gauge is a must. The response team is deployed when there is a glitch in data transferring and obvious unusual SCADA data. When one rainfall gauge has malfunctioned, calculation of average area rainfall for the catchment using the inverse distance method based on the neighbouring rainfall gauges is conducted. As the rainfall gauges are within a radius of 3 km from each other, the availability of fine spatial data allows for an accurate approximation of rainfall.

11.3.5 Design of monitoring networks

An overview of the locations of rainfall gauges and measuring stations dedicated to SMART operation is shown in Figure 11.6. Data at the upper catchment of the Klang River serve as an indication of a downstream flooding scenario, which provides ample time for appropriate SMART operational actions. The time between peak flow from upper catchment to the critical confluence of the Klang/Ampang Rivers takes about 30–60 minutes, depending on the rainfall intensity of a storm event.

The annual cost of operation, including flood detection, flood flow components, and housekeeping can become close to RM 4–6 million (€ 0.80–1.21 million). A significant fraction of the operational cost is attributed to the pumping and control gates. There are 25 gates installed within the SMART system to control the systematic conveyance of excess stormwater within the tunnel, including two gates (i.e. NJB and SJB gates) specified for the traffic tunnel (Figure 11.7). During Mode 3, the NJB (north junction box) and SJB (south junction box) gates are closed. The maintenance of the instruments can reach up to RM 700–800 thousand (€ 140–160 thousand) in a year.

11.3.6 Operation and maintenance

The SMART facility runs 24/7, all year long. In ensuring minimum problems in data monitoring and storm management, monthly preventive maintenance is mandatory for all instruments discussed in Figure 11.6. Maintenance for each measuring station follows the checklist prepared by DID to guarantee a thorough inspection and correct protocol. The systematic calibration procedure for each instrument is conducted quarterly by an accredited calibration agency. Calibration work for water level sensors must comply with the procedures set and is controlled by the quality management system ISO 9001:2015 (ISO, 2015; Cert

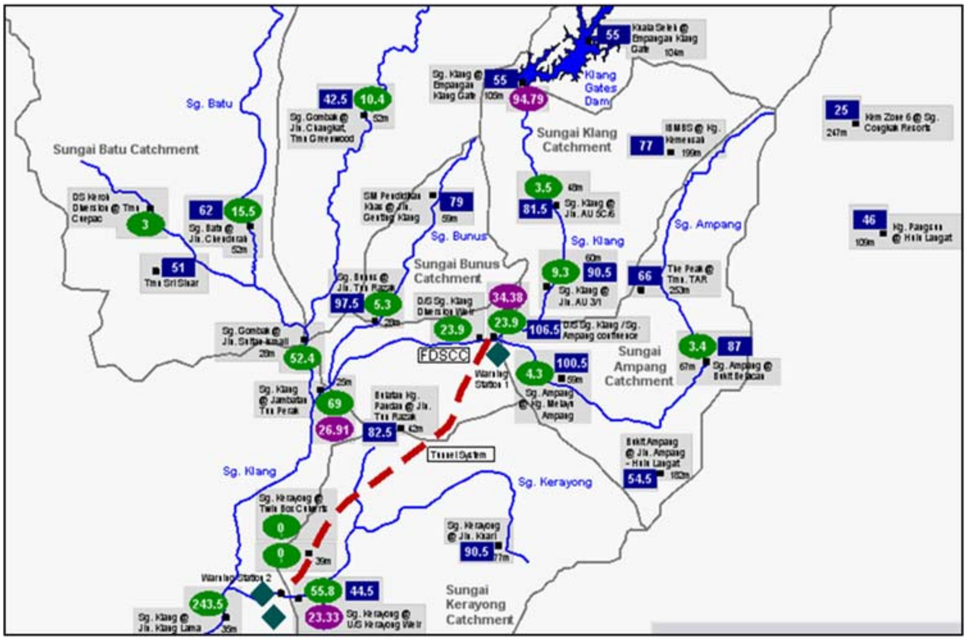

Figure 11.6 A snapshot of the monitoring network within the Klang River catchment, specifically for the operation of SMART. Data for rainfall, water level, and flow velocity are displayed in blue, green, and purple boxes, respectively. The dashed thick red line indicates the SMART Tunnel alignment. *Source*: Department of Irrigation and Drainage, Malaysia.

no: QMS 02621). Immediate corrective action is administered for repairing malfunctioned equipment and pressing issues such as missing data during storm events.

Guidelines for safety and health relating in operating and maintaining the hydrometeorological equipment are available in the HP32 (for rainfall – DID, 2018a) and HP33 (for water level – DID, 2018b) documents. Maintenance work of the telemetric unit, testing, and validation of water level sensor, repair, and services of hydrological equipment is properly recorded using standardized forms.

The safety of the instruments at the station is safeguarded by constructing non-climbing, anti-cut and wired gates. The locking system is installed at both the entrance gate and station door to minimize illegal public trespassing.

11.3.7 Uncertainty assessment and data validation

There are 22 rainfall gauges in the network, which are dedicated to cover an area of 596 km^2. These rainfall and water level gauges are point measurements. Therefore, the extensive rainfall and water level gauges are designed to capture the spatial and temporal variations of any storm events, given that Malaysia is a tropical country that is likely to experience frequent storms resulting in a significant amount of rainfall, especially in April and October, i.e. inter-monsoon seasons (see Muhammad *et al.*, 2016).

SMART's hydrological monitoring system is vulnerable to error due to wind and the type of instruments. The tipping bucket may underestimate the rainfall amount due to the bucket tipping action, especially during extreme storm events. Other than that, systematic wind field deformation above the gauge orifice may cause a 2% to 10% systematic error (WMO, 2008). Although these errors cannot be eliminated completely,

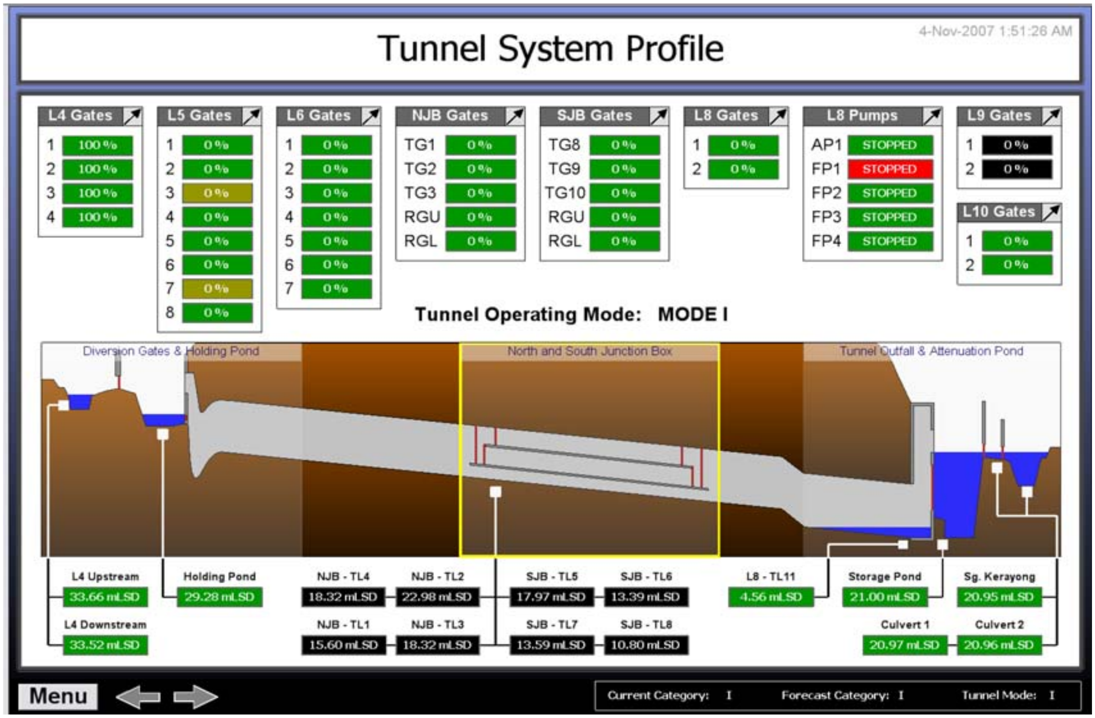

Figure 11.7 A snapshot of operational display Mode 1, showing the operational status of the gates installed along the tunnel. Note: NJB and SJB gates are for the traffic tunnel. *Source*: Department of Irrigation and Drainage, Malaysia.

periodic instrument maintenance and calibration and continuous assessment of observed hydrological data are highly crucial to ensure the error and data uncertainty are minimized.

11.3.8 Challenges, lessons learnt

The booming development of Kuala Lumpur and rapid expansion of the urbanized area is increasing the runoff (and with a shorter time) into the main stem of the Klang River. The climate change phenomenon has also contributed to more frequent storm events with higher rainfall intensities. Due to the scale, magnitude and sensitivity of SMART, the number of rainfall and water level gauges available in the catchment should follow the recommended minimum station densities for hydrology given by WMO (2008), i.e. one station per 10–20 km^2 of the catchment area. The use of advanced hydrological monitoring equipment and technology, such as radar, remote sensing, and satellite observations should also be explored to increase the accuracy and quality of observed data and minimize data uncertainty, particularly for the GIS data. An updated map of Kuala Lumpur and Selangor, and details of changes of land use within the Klang River catchment is essential to ensure a reliable and high accuracy runoff volume (for modelling).

An increase in the frequency of flood events (both fluvial and pluvial) within Kuala Lumpur poses challenges to the local authorities in the adaptation of managing stormwater and minimize flooding scenarios at the critical strategic areas of Kuala Lumpur, particularly the commercial zones. Data indicate that the operation of SMART is facing more challenges during the El-Nino season due to the high occurrence of extreme rainfall events. Higher frequency of flood operations was observed compared to the lower rainfall events and subsequently fewer flooding incidents during the drier La-Nina season. Extreme high precipitation events in Malaysia correspond with the occurrence of El-Nino-Southern Oscillation (ENSO) (commonly known as El-Nino) whilst the significant decrease in wet events is due to the La-Nina, during the months of December-January-February (Tangang *et al.*, 2017). ENSO is the irregular, periodic variation of sea temperature and winds over the tropical eastern Pacific Ocean, which has been extensively studied to be well correlated with extreme precipitation events (Casanueva *et al.*, 2014). Learning from experience, particularly during the El-Nino season, rigorous hydrological modelling is conducted to assist in smoother SMART operations.

11.4 WICKS RESERVE BIORETENTION BASIN, THE BASIN, VICTORIA, AUSTRALIA

11.4.1 Scope and objectives

Wicks Reserve bioretention basin was built in 2011 in the eastern suburbs of Melbourne, Victoria, Australia to protect the local stream against the impact of urbanization. This basin (Figure 11.8) was monitored to inform and validate policies as the construction of such basins is becoming widespread across the Melbourne area. Construction and monitoring were financed by Melbourne Water (the local water manager) and Knox City Council. Monitoring has been conducted by the Waterways Ecosystems Research Group (WERG) of The University of Melbourne. The aims of the monitoring programme were (i) to assess the hydrologic performance of the basin (reduction of stormwater volumes and peaks), (ii) to assess its water quality treatment performance and (iii) to monitor the fate of infiltrated stormwater from the basin to the nearby stream. Research was the primary driver for setting up the monitoring system, which will be dismantled when the research project ends (monitoring started in March 2013, with probes

Figure 11.8 Wicks Reserve bioretention basin. *Source*: Jérémie Bonneau (INRAE).

being installed in 2013 and 2014. Flow monitoring was stopped in 2018 and groundwater monitoring was stopped in December 2019). Monitoring has not led to direct policy changes.

11.4.2 Recorded data

11.4.2.1 Rainfall data

Rainfall was monitored onsite using an *Odyssey* Logger with a tipping bucket rain gauge (NZ$ 369 ~€ 215 – all prices are given as of June 2019), clear from canopy interception. The rain gauge was inspected weekly to fortnightly to verify that the hole of the rain gauge bucket was not blocked (i.e. by leaves). If the rain gauge was found to be partially blocked, the cumulative rainfall was compared to another nearby rain gauge. Blockages are obvious on such graphs. If the hole was found to be completely blocked with no water reaching the tipping pivot, data since the previous download were considered not usable. Rainfall was recorded at a 1-min timestep in the built-in logger. Total blockages were rare. The rain gauge did need calibration: the volume of rainfall was collected every month, weighed to 0.1 g accuracy and compared to the number of tips given. While the manufacturer-claimed measured depth was 0.2 mm of rainfall per pivot tip, calibration showed that a factor of 1.1 needed be applied to the data (i.e. the actual tip was 0.22 mm). This calibration factor was checked monthly to check for any drift. Most data (>95%) were usable.

11.4.2.2 Flow data

Flows going into and out of the basin were monitored using area-velocity sensors connected to *Hach Sigma 950* flowmeters (hereafter referred to as HACH). The probes recorded velocity with a Doppler ultrasonic sensor and water level with a pressure diaphragm. Monitoring of flows proved very challenging. Small weirs had to be installed in two pipes to make sure the probes remained submerged to better monitor low flows, which was very important to close the water balance. Both inlet pipes were large and likely oversized (750 and 525 mm in diameter) to accommodate high storm flows, but this proved challenging for flow monitoring as large pipes resulted in low water levels. Catchment hydrographs had long tails, with substantial and long-lasting low flows (<1 L/s). Flows (level and velocity) measured were within manufacturer-claimed accuracy ranges (−1.52 to 6.1 m/s for velocity, 0–3 m for level). Flowmeters were manually calibrated regularly (twice a year), using an electro-magnetic flowmeter for high flows and a bucket and a stopwatch for low flows. Rating curves were constructed to correct the probe readings, which demanded a substantial amount of work. A fire hydrant was connected to an electro-magnetic flowmeter and water poured into the stormwater pipes where the flowmeters were located. As such it was possible to compare the flow value given by the electro-magnetic flowmeter and readings (flow, level, velocity) given by the flowmeters in the pipes. This allowed the construction of rating curves (e.g. measured flow or level or velocity vs. observed flow) to correct the values given by the flowmeters. For low flows (<5 L/s), the rating curves were completed with manual measurement of the actual flow, measured by a bucket and a stopwatch. Flow data were stored in a built-in logger, at a 6-min timestep. Sediments caused issues with flowmeters at the inlet of the basin, resulting in very large chunks (>50%) of data deemed unusable, after discussion between researchers, for one inlet probe. The sediments were cleaned regularly, when they had accumulated on top of the probe.

11.4.2.3 Water quality (autosampling)

Two autosamplers (Sigma 900 MAX portable, with 24 × 1 L samples) were installed at the inlet and at the outlet of the basin to monitor the water quality treatment performance of the basin. The autosamplers were connected to the flowmeters and samples were taken every given volume to cover a large range of hydrographs. Such samplers were required to be turned on manually before a rainfall event and samples were collected and sent to the laboratory for analysis within 24 hours of sampling.

11.4.2.4 Water and groundwater level data

Water level at the surface of the basin was monitored with four *Odyssey* capacitance probes, chosen primarily for their price and availability (NZ$ 248 ~ € 140). The water level within the filter media of the basin was monitored using three of the same *Odyssey* capacitance probes. The fate of infiltrated stormwater was monitored with 15 water level probes (the same *Odyssey* capacitance probes), installed around the basin to monitor shallow groundwater (ranging 2–5 m deep). All these probes were calibrated in the laboratory before deployment. Calibration was checked and adjusted when needed. Because of their relatively short length, it was easy enough to remove every probe from their bore during download to clean them and check the calibration with a home-built 2-m long PVC pipe filled with water. The operation took about 2 hours for all probes, so missing data during downloads were minimal. Water levels were read with an accuracy ranging from 2–5 mm, and most data were usable, except for times with flat batteries or unexplained probe issues (around 10% of the dataset).

11.4.3 Maintenance, operational cost

The site was visited weekly or fortnightly for routine checks and maintenance operations (replacement of flat batteries, faulty probes, collection of water quality samples, calibration of probes, cleaning of probes, checking flowmeters, etc.). Overall monitoring was costly in operational time. The site and data were mostly managed by a PhD student (50% of his/her time) assisted by two technicians (around 0.5 days a week each).

11.4.4 Database, accessibility and data management

Data were downloaded from the loggers, on site, every month, the operation taking about half a day to a day of work. All data were downloaded on a computer and then stored into a *Dropbox* folder shared by all members of the WERG. The folder was only accessible by researchers from the group. The *Dropbox* folder contains data of all projects of the WERG and is managed by a data manager, funded by the partnership between the WERG and Melbourne Water. The primary responsibility of the data manager is to look after data from all WERG projects. Data validation was done by or with researchers who spend time on sites. Data format and data storage were systematic and the same for all probes (flow, water level, …). Data were stored in three folders:

- Raw data, containing the files obtained from the sensors. These files were never touched, never modified.
- Compiled data, containing data being processed (validation, correction…).
- Final data, containing validated data (in either.csv files or .r data format), ready to be read and used in R for data analysis.

Additional but crucial data validation was done manually using field notes and observations to adjust data when needed. A *quality code system* was set up as: 1 (good data), 2 (data might have a problem) or 3 (unusable), based on field observations (for example, if a wooden stick was observed on the probe but data still made sense and visually looked OK, the quality code would be 2). Researchers shared a spreadsheet where timings, all field observations and actions taken for the probes were recorded so that anomalies in the data could be explained later on (for example: 'on this day, probe nr x has been removed from its casing to sample groundwater', can explain a couple of timesteps containing surprising data). Data are available upon request pending agreement of the researchers who collected them and pending specific conditions on the use of data. Some data collected at this site have been shared with research teams across the world (USA, Chile, Australia, France) for potential collaborations.

11.4.5 Power management

Water level probes were powered by two built-in AA 3.6 V lithium-ion batteries that were replaced when needed (every 1–2 years on average). Flow meters and autosamplers were powered by 12 V batteries that were checked and replaced when needed with batteries charged in the WERG workshop. Due to the workload involved, a battery charger was later connected to the main electric grid, and 12 V cables were run from this point to the batteries. Such a solution is ideal because running 12 V cables does not involve licensed expensive and dangerous electrical work.

11.4.6 Health and safety

Site visits were performed under the health and safety guidelines of both *Melbourne Water* and the *University of Melbourne*. *Melbourne Water* mandates its collaborators to possess a permit obtained after taking an online class and a subsequent test (even though this basin is not a *Melbourne Water* asset – it is a council asset). The University of Melbourne employees and students are mandated to complete a Risk Assessment specific to dangers of the site visited and the tools used or the tasks performed on site. Each new staff or student must review and sign this Risk Assessment before coming on site. This document covers safety issues for general fieldwork and work specific to this particular site and project (never be alone on site, wear personal protection equipment, snake bites, aggressive sun, heat). For more detailed, rare or high-risk tasks (e.g. going into a pit), researchers are required to complete a Task Risk Assessment (TRA) specific to this particular task.

11.4.7 Reporting

Contact between the University's researchers, council engineers and *Melbourne Water* officers (the overarching authority) was very frequent with regular update meetings and very frequent emailing. Scientific papers were published (Bonneau *et al.*, 2018, 2020) or are in the making. Data were presented at international conferences, and at several presentations with industry partners. An intern was hired in 2017 to put together a monitoring report for *Melbourne Water*.

11.4.8 Lessons and suggestions

The monitoring set-up at this site required constant human inputs and labour with at least weekly site visits, indicating that a remote way to communicate with probes would save operational time.

Meta-data (information about sensors, calibration, field notes) are crucial to data management and analysis, as they allow understanding of why chunks of data look suspect. The way meta-data will be recorded and used should be discussed during planning a monitoring strategy. Similarly, processing and analysing data as early as possible after collection (instead of storing long periods of data without looking at them) can avoid further trouble as many issues with probes were identified during data analysis. In this case study, weeks of data were lost before realizing that low flows were important and that therefore weirs had to be installed, and that the flowmeters needed substantial calibration effort to provide reliable data. This was all found by trial and error.

Original aims of the monitoring were achieved and stakeholders (research, council, water authority) were pleased with the monitoring results. Reliable experimental assessment of the hydrological and water quality performance of the basin was obtained. To date, monitoring of this site has not yielded actual policy changes, but has enhanced confidence amongst stakeholders to implement such systems across the Melbourne area.

11.5 FLOW MONITORING CAMPAIGN FOR COMPANY-WIDE INTEGRATED URBAN DRAINAGE MODEL UPGRADE, ANGLIAN WATER SERVICES, UNITED KINGDOM

11.5.1 Overview

Anglian Water Services (AWS) have adopted an integrated supply chain and holistic approach for their AMP6 (AMP6 stands for Asset Management Plan 6. This is the UK water industry financial cycle running from 2015 to 2020) Integrated Urban Drainage (IUD) Modelling Programme. The key objectives of the IUD Programme comprise working collaboratively with all partners and within the business to deliver 100% coverage of urban drainage models to a level of confidence appropriate for intended use. Focusing on the key metrics of flooding and pollution which are common performance commitments across all water companies, these assessments have included amongst others, catchment performance and risk assessment as part of the preparation of Drainage and Wastewater Management Plans, asset health assessments at critical ancillaries such as pumping station failure analysis, the impacts of future catchment changes such as growth, climate change and urban creep and ultimately, to define a catchment strategy to mitigate all of these risks.

The IUD Programme entailed systematic assessment of existing models and risks across all AWS's catchments, risk-based planning and execution of asset and short-term flow surveys, and subsequent model upgrade and re-calibration based upon the base data and the data collected through recent surveys.

This case study focuses on the flow survey component of the IUD Programme. Information about other components of the programme can be found in Brayshaw & Wilkes (2016). Note that, in addition to the short-term flow surveys undertaken as part of this programme, see WRc (1987) for information on this type of survey, permanent monitoring at strategic sewer locations, overflows and other ancillaries is also undertaken by AWS. The permanent monitoring falls outside of the scope of this case study.

11.5.2 Risk-based flow survey planning

Survey planning entailed initial screening of all Anglian Water catchments, based on assessed risk, followed by actual flow monitoring scoping following cost-benefit principles. Figure 11.9 shows a map of the region where Anglian Water Services operates.

The initial catchment screening (referred to as Model Delivery Milestone 1 – MDM1) considered factors such as growth, pollution and flooding occurrence. This resulted in 447 urban drainage catchments to be considered in the second stage (MDM2).

MDM2 consisted of a high-level scoping of flow monitoring needs for the catchments of interest. Monitor numbers were derived by looking at the total length of all the sewers in each catchment and the number of ancillaries with the potential to cause pollution, mainly combined sewer overflows (CSOs) and pumping stations. The rough criteria used was one monitor for every 1 km of pipe, plus one additional monitor per overflow. For example, a catchment with circa 10 km of sewer pipes and five CSOs would be assigned a minimum of 15 monitors.

Monitoring needs were then compared against available budget, in turn based on a preliminary cost estimate, assuming a 12-week duration per survey. The time required to complete all the surveys (including planning, installation, monitoring and decommissioning) was also considered and when programmed it was obvious that it was not time efficient to undertake many small surveys. At this point

Figure 11.9 Map showing the operational area of Anglian Water Services, which comprises 28,000 km^2. *Source*: Anglian Water Services (2019) Anglian Water's Cross Sector Infrastructure Access Statement, March 2019. https://www.anglianwater.co.uk/siteassets/developers/development-services/cross-sector-infrastructure-access-statement---march-2019.pdf (accessed 28 April 2021).

a decision was made to remove small, low priority catchments from the monitoring campaign. Instead, for these low priority catchments, existing telemetry (SCADA) data at ancillaries (AWS's SCADA system comprises telemetry sensors at key ancillaries, which provide real-time performance metrics e.g. water levels at wet wells, pump status, treated effluent flow rate) alongside radar rainfall data were adopted for model calibration. These catchments were mainly in locations where drivers such as growth were not as highly ranked at MDM1 stage, but which were still relevant to AWS's business needs for the next AMP cycle (AMP7). The final number of catchments that had a new flow survey carried out was 143.

For the selected 143 catchments, site selection for each flow monitor was made with potential hydraulic conditions, access requirements and health and safety (H&S) in mind. For example, locations on bends in the network and chambers that may have turbulent conditions were avoided. The initial selection was automated through SQLs in Infonet (asset database). Accounting for the above-mentioned considerations improved the likelihood that, when the site engineers came to install the monitors, the location would be suitable for accurate data capture. It was also crucial during the selection of sites that traffic management and site access were accounted for, avoiding locations where costly traffic management would need to be put into place to install and remove the monitor, or where access to manholes would be difficult due to access restrictions on private land. In catchments where we had access to information on historic flow surveys, we installed monitors in the same locations where we could confirm that the data captured previously were of an acceptable standard. This increased the likelihood that it would be possible to install the monitor, and the hydraulic conditions would lend themselves to accurate data capture. Details on H&S factors considered during survey planning can be found in Section 11.5.4 below.

Table 11.3 WaPUG code of practice recommended rain gauge densities for short term flow surveys (updated version: CIWEM, 2017).

Type of terrain	Typical number of rain gauges
Flat	1 + 1 per 4 km^2
Average	1 + 1 per 2 km^2
Mountainous	1 + 1 per 1 km^2

Flow monitoring was accompanied by rainfall monitoring using tipping bucket rain gauges. Rain gauge densities (Table 11.3) were decided upon following WaPUG (UK Wastewater Planning Users Group, now CIWEM Urban Drainage Group) criteria (CIWEM, 2017).

A total of 3,568 flow and/or depth monitors and 801 rain gauges were installed between March 2017 and November 2019. The aim for each flow survey (with each one of the selected 143 urban drainage catchment areas having one individual flow survey done) was to capture three WaPUG compliant storms (WaPUG compliant storm events must have total rainfall depth ≥5 mm, rainfall intensity ≥6 mm/h for more than 4 minutes, and should ideally display limited spatial variability, to ensure that the rainfall field can be well represented based on rain gauge measurements) and two dry weather days, one on a weekend and one on a week day. This enabled urban drainage model calibration and verification in line with WaPUG guidelines. Achieving this target across the vast number of monitors installed was not easy and required adhering to a detailed programme of works. In some cases, when the flow survey had been in the ground for a period of more than 12 weeks, storm events that had only a partial number of monitors pass the WaPUG criteria were then accepted as viable events. This helped to ensure that prolonged dry spells did not significantly impact the programme of works.

11.5.3 Monitoring system – technical specifications

As indicated above, a total of 3,568 monitors and 801 rain gauges were installed between March 2017 and November 2019 as part of AWS's monitoring campaign. Technical specifications of the sensors, data loggers and data transmission, storage and management system are given next.

11.5.3.1 Flow monitoring

Generally, two in-sewer flow attributes were monitored: depth and velocity. Based on depth and velocity measurements, alongside conduit geometry, it was possible to estimate flow rates. It is worth noting that, depending on the monitoring purpose and site characteristics, at some locations only depth monitoring was undertaken.

Three types of in-sewer sensors were used in the monitoring campaign:

- *Detectronic multi-sensor flow meter* (MSFM), which includes ultrasonic velocity, pressure depth and (optional) ultrasonic level.
- *Technolog Cello 4S with depth pressure sensor*.
- *Technolog Cello CSO ultrasonic depth recorder*.

The three sensors are encapsulated to withstand harsh environments and can be used to monitor raw sewage, industrial effluent and stormwater. Likewise, the recording frequency is programmable between 1 s and 1 h.

In the case of the AWS's surveys, a logging frequency of 2 minutes, which is the UK industry standard, was adopted.

The MSFM sensor was used at approximately 90% of the locations, as it is the only sensor out of the three sensors used in the survey which can monitor velocities and depth, thus allowing flow calculation which was required in the vast majority of sites. The Cello depth sensors were used at locations where only depth monitoring was needed (e.g. at some CSOs and tanks) or where the MSFM monitor was unsuitable, with the limiting factor of the MSFM monitor being the range in which it can accurately monitor depths (i.e. a maximum of 3.5 m). Generally, the Cello pressure sensor was used more often than the ultrasonic one. In fact, the ultrasonic sensor was only used at a handful of locations where the site conditions did not allow for the installation of a pressure sensor (e.g. due to access and/or flow conditions).

11.5.3.2 Rainfall monitoring

Rainfall across the catchments subjected to flow monitoring was measured by means of tipping bucket rain gauges equipped with GPRS data loggers. Key rain gauge and data logger specifications are summarized in Table 11.4. As mentioned earlier, rain gauge densities were decided upon following WaPUG guidance (Table 11.3).

The reader must be reminded that for catchments not subjected to short-term flow monitoring, available telemetry data (i.e. SCADA depth and flow records at ancillaries) and radar rainfall data were used for model re-calibration. The radar data used for this purpose were the UK Met Office data, available at 1×1 km^2 and 5 min resolution from the CEDA archive (http://ceda.ac/uk/, accessed 17 Dec. 2020).

11.5.3.3 Data transmission, storage and retrieval

In-sewer monitors and tipping bucket rain gauges were equipped with GPRS data logging and transmission units.

Data from each logger were transmitted on a daily basis via a 2G network to a central physical server. All loggers were set to transmit data from 6 a.m. every day. The logger would attempt to send data for up to 3 hours after the first attempt but would then cease in order to conserve battery life. Once in the server, data could be visualized via the RPS Flow Survey Online Viewer. The reason data were transmitted only once per day, rather than at a higher frequency, was to preserve battery life.

It is worth noting that data transmission issues – related to poor signal – were encountered in approximately 35% of all monitoring sites. Data from the problem sites were retrieved manually on a weekly basis; this entailed renewing traffic permits at traffic-sensitive sites. The weekly retrieval frequency allowed timely data review, and therefore timely maintenance, and avoided filling up the

Table 11.4 Technical specifications of tipping bucket rain gauges and data loggers.

Description	Units
Bucket size	0.2 mm
Catchment area	400 cm^2
Accuracy	±1% at 26 mm/h
Logging frequency	Variable – time of tip
Storage capacity	In a practical sense unlimited

loggers' internal memory. The memory capacity at 2 minutes logging rate, as is the case for flow monitors, is approximately three weeks.

Final datasets were available in FDV format. Data in this format can be readily imported into RPS' data processing and hydraulic modelling software packages, i.e. FlowBot data processing toolbox (described below) and InfoWorks.

11.5.4 Health and safety management

Health and safety (H&S) considerations were kept in mind throughout all survey stages, including survey planning, installation, operation, maintenance and decommissioning.

During survey planning a desktop-based hazard screening was undertaken for every monitor location, including preferred and alternative locations. In the case of in-sewer monitors, to be installed via manholes, consideration was given to the specific risk of the location. For example, no locations on roads with speed limits of over 30 mph (48 km/h) (unless locations were rural) were planned and locations such as major junctions, pedestrian crossings and roundabouts were avoided. Likewise, consideration was given to access, proximity to emergency services and schools, manhole depth (with too large depths avoided and/or marked for inspection) and pipe size, amongst other factors. In the case of ancillaries (e.g. CSOs, pumping stations, treatment works), consideration was given to factors such as site configuration and presence of electrically-powered elements.

Once potential monitoring locations were identified, pre-installation surveys were carried out. These consisted of visiting the potential monitoring sites to determine if they were suitable and safe to install in. For in-sewer monitors, only manholes classed as low or medium risk and having direct line of sight to the person entering were selected for installation (i.e. NC1 and NC2 sites as per Water UK National Classifications (NC) for Confined Space Entries (Water UK, 2019)). In the case of complex ancillaries within AWS compounds, survey contractors were required to complete site induction upon arrival and to consult with operatives to decide on the safest plan of action. During these visits, gas monitoring was performed at all times, even if a confined space entry was not going to be made. The gas monitor would be lowered into the manhole and/or around the ancillary to ensure that it was safe to stand over it to look inside to assess the site's suitability for flow monitoring. In addition, one operative would have PPE (personal protective equipment) on for a confined space entry as it is not always possible to assess the site from above. During those visits' access/egress was assessed, including review of dimensions to ensure safety of the configuration, and depth of flow was estimated with sites with water levels deeper than 500 mm being discarded on safety grounds.

At the end of the pre-installation stage, an installation plan was formulated for each catchment. Based on assessed risk, monitoring sites were classed as 'generic' or 'site specific'. The 'generic' category generally covers NC1 and NC2 manholes (for installation of in-sewer monitors) and rain gauge locations. The 'site specific' category generally covers complex ancillaries. For 'generic' sites, standard risk assessments and method statements (RAMS) were prepared for installation, while for 'site-specific' monitoring locations customized RAMS were prepared for each site. Installation was generally carried by 3-man crews, following the corresponding RAMS.

Once the surveys went live, survey contractors and hydraulic modellers assessed monitor performance on a weekly basis (more details in following section). Any sites identified as performing poorly, either due to sensor malfunctioning or site characteristics, were flagged up and maintenance was undertaken following the corresponding RAMS.

Survey progress in terms of storm event and dry day recording was also reviewed on a weekly basis by hydraulic modellers. Once three WaPUG-compliant storm events and two dry days had been successfully recorded at a given catchment, a decision was made to terminate the given survey. Monitor decommissioning was carried out following the corresponding RAMS.

11.5.5 Data quality assurance during and after monitoring period

Flow and rainfall monitoring data were assessed on a weekly basis as well as at the end of the survey period using RPS' in-house FlowBot toolbox.

FlowBot is a bespoke software solution that can be utilized by both flow survey data analysts and hydraulic modellers to visualize, manage and understand flow survey data. FlowBot allows undertaking a range of checks on the depth and flow measurements, including flow monitoring data comparison against theoretical depth vs. flow rating curves, flow monitor comparison including volumetric checks between upstream and downstream monitors, and automatic identification of dry weather and storm events based upon user-defined criteria. Many of these checks are in line with those recommended in the Guide to Short-Term Flow Surveys (WRc, 1987). In addition, FlowBot allows for the deployment of a machine learning algorithm (decision tree-based) to classify the performance of flow and depth monitors and ultimately identify faulty measurements. The machine learning algorithm has been trained using 30,000 days of previous human classifications, mined from previous RPS flow surveys. The outputs that are generated have a high degree of accuracy, with assessments that would usually take hours being completed in minutes. Automating this user-intensive operation reduced the time spent by engineers classifying data and allowed for more time to be spent proactively managing a flow survey, maximizing the quality of the final data. In addition to depth and flow checks, FlowBot includes features for rain gauge data quality assurance via cumulative rainfall plots.

On the whole, the use of the FlowBot toolbox led to 80%-time savings in the processing of flow survey data, in relation to conventional (more manual) methods.

By undertaking weekly assessments while the survey was still on the ground, it was possible to detect and rectify any problems with given monitoring locations throughout the survey and ultimately ensure that good quality data were collected at the locations of interest. Problems encountered with monitors included power failure, transmission problems due to poor network coverage and/or location of the monitor inside sewer network, ragging, flow/depth data below monitor resolution, and rain gauge blockages, amongst others. Some of the problems could be rectified through sensor maintenance. Others required sensor re-location. Ultimately, quality assurance of flow survey data ensured that the best data possible were adopted for model calibration and verification.

11.5.6 Conclusions and outlook

As part of Anglian Water Services' AMP6 Integrated Urban Drainage Modelling Programme, short-term (average of 12-weeks duration) flow and rainfall surveys were undertaken across the majority of the company's catchments, resulting in a total of 3,568 flow and/or depth monitors and 801 rain gauges being installed and operated between March 2017 and November 2019. The data collected through these surveys enabled standardized re-calibration of hydraulic sewer models to a level of confidence appropriate for intended use. The resulting models, alongside other company datasets (e.g. permanent monitoring data at strategic locations), will enable a range of catchment performance assessments and implementation of management strategies, which will ultimately lead to improved catchment management.

The magnitude of this project required a systematic approach and enabled development of survey planning and execution, and data quality-assurance tools, which delivered significant efficiencies and ensured collection of high-quality flow survey data. In particular, the magnitude of the project enabled extensive validation with Machine Learning (ML) tools for data quality assurance, which were shown to provide an efficient alternative to time-consuming manual data review.

Likewise, essential to the delivery of this project was the collaborative work across different business units and with external partners, including survey and hydraulic modelling contractors.

Problems encountered throughout these surveys included, amongst others, poor signal at approximately 35% of the sites (in which cases data had to be manually retrieved) and difficulty in capturing the three WaPUG-compliant storm events within the envisaged survey duration (i.e. 12 weeks) in some of the catchments. Likewise, maintenance of and data removal from traffic sensitive sites required constant renewal of traffic permits, which was time-consuming. These problems were however tackled with proactive data review and effective work-planning and collaboration between the modelling and survey teams.

The data collected as part of these short-term surveys will be stored centrally by AWS, both to provide an audit trail as well as to enable future studies such as detailed flooding and pollution investigations, further development of ML-based data assurance tools, preliminary testing of real-time analytics, amongst others. UK Water Utilities normally keep their short-term flow data in-house, and not publicly available. Depending on the type of data and the sensitivity of the catchment, access may be arranged for research on a case-by-case basis, through individual legal agreements with the researchers. Some higher-level aggregate longer-term monitoring data are available publicly through OFWAT's annual performance reports (https://www.ofwat.gov.uk/regulated-companies/company-obligations/annual-performance-report/, accessed 28 April 2021).

11.6 IMPAKT! – OPTIMIZATION OF THE URBAN DRAINAGE SYSTEMS IN THE DOMMEL AND WARMBEEK RIVER SUBBASINS, FROM A RIVER QUALITY POINT OF VIEW, FLANDERS, BELGIUM

11.6.1 Scope and objectives

The IMPAKT! Project (https://www.grensregio.eu/projecten/impakt, in Dutch, accessed 28 April 2021) aims at defining measures to reduce the impact of wet weather urban discharges on the receiving rivers' water quality and ecology. The two river subbasins Dommel and Warmbeek comprise five drainage areas and five municipalities. The definition of the optimal measures is to result from scenario analysis on a set of integrated and linked models (sewer system, WWTP, receiving water). An extensive sewer flow and sewage quality monitoring campaign was set up with a view to both validating the different models and keeping them up-to-date in the years to come. Furthermore, it is expected that thorough analysis of the many measurement data will allow the optimization of the many pumping stations and storage basins.

11.6.2 Measured variables and location of monitors

A total of 75 monitoring sites have been defined throughout the project. As budget constraints did not allow for parallel monitoring at all locations, the project was designed to work with a rotation system for (part of) the sensors. This is reflected in the design of the used database. The average period for which monitors had been operated at one individual site for rotated devices was between 9 and 12 months. This period was chosen to capture seasonal variations and as a result of practicalities. The absolute minimum for monitoring at one location is deemed to be around 3 months. First sensors were installed in March 2017. As of July 2020, about 35 locations were still active without any plans for de-installation.

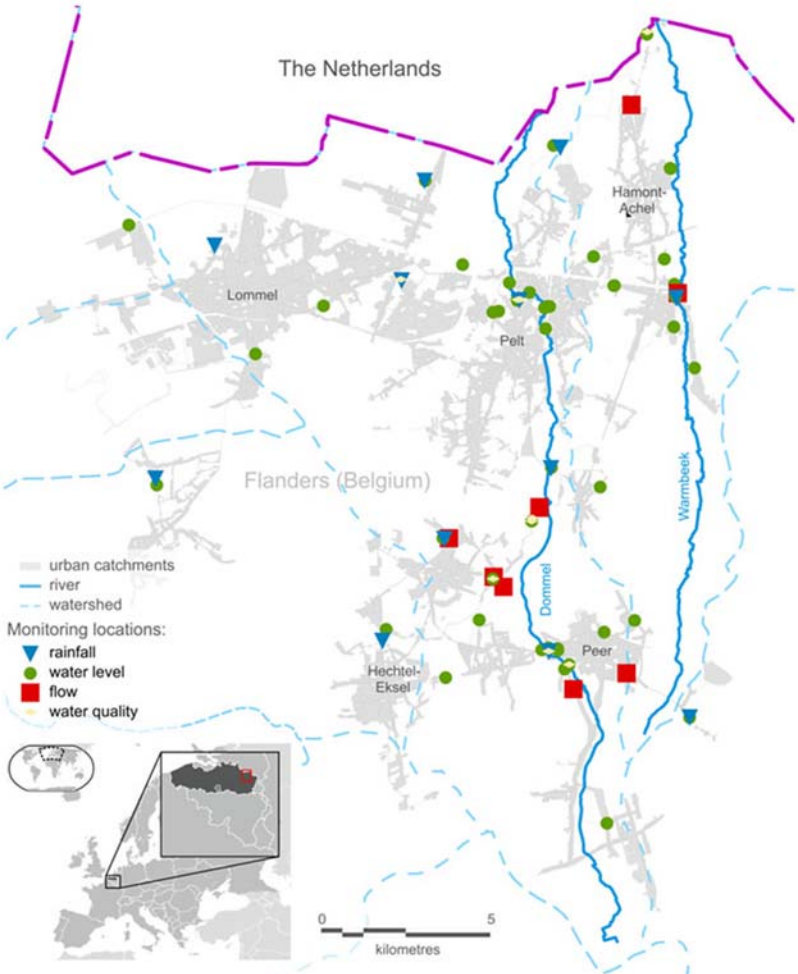

Figure 11.10 Monitoring locations in the project area of the municipalities Lommel, Hechtel-Eksel, Pelt, Peer and Hamont-Achel (Flanders, Belgium); lower left: case study location. *Source*: adapted from https://nl.wikipedia.org/wiki/Vlaanderen#/media/Bestand:Flemish_Community_in_Belgium_and_Europe.svg (accessed 28 April 2021).

Figure 11.10 shows an overview on the finally selected locations for flow, water level and precipitation, but also continuous water quality monitoring (temperature, conductivity, turbidity, TSS (total suspended solids), BOD (biological oxygen demand), COD (chemical oxygen demand), NO_3, NH_4, all backed up by lab samples) not detailed here any further.

11.6.2.1 Flow and water level

Flow is monitored at 13 locations using 10 devices based on proven technology: hydrostatic depth transducer and ultrasound Doppler velocity sensor. Such devices have been successfully used throughout many short-term campaigns over the last 20 years (using an external contractor). Usually the focus of short -term campaigns, which typically run for seven weeks with preferably a minimum of three reasonable rain events being monitored (WRc, 1987), is on the characterization of the system's most relevant locations and ancillaries (e.g. large CSO structures, throttle locations, pumping stations and joining points of collectors) to develop a sound understanding of systems hydraulics. In the IMPAKT! Project this classic approach was maintained for much longer (approx. 1.5 years) to allow for the identification of seasonal variations in dry weather flows, and to allow rotation between a number of locations.

The data gathered by the flow monitoring campaign are extended through the permanent installation of 20 additional water level monitoring devices (pressure gauges) at CSOs (in collectors and/or storage tanks), and 15 data loggers capturing existing level measurements in pumping stations. At these locations full flow monitoring is of less or no relevance given the poor velocity conditions, but levels monitored at pumping stations can be converted using the wet well's geometry to estimate flows as done by Fencl *et al*. (2019).

Desirable monitoring locations are selected based on detailed analysis of the existing sewer models or asset databases. Ideally, more than one potential monitoring location is identified for the same purpose. All potential monitoring locations to be maintained in-house are visited by a team of modeller(s), desk personnel in charge of sensor operation and the technician(s) responsible for installation and maintenance in order to evaluate their suitability for the monitoring task at hand and possibilities for sensor installation. Discussed criteria were, depending on locations: required safety measures to be taken for installation/maintenance, (lack of) options for sensor positioning, relevance and representativeness of the location for the process to be monitored, expected disturbances, requirements for sensor configuration (offset set-up).

Monitoring location choice is paramount. During dry weather, monitoring locations situated several kilometres downstream of a point of high impact will still reflect upstream influence as shown in Figure 11.11.

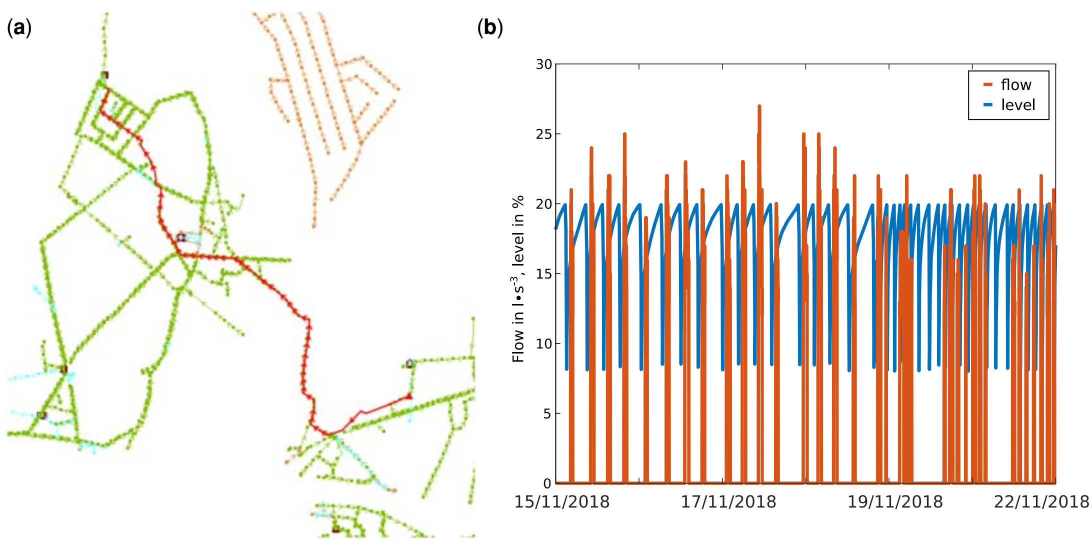

Figure 11.11 The change in the dry weather pattern in a pumping station is traceable 3.5 km downstream in a downstream flow monitoring location; (a) flow path between discharge point and monitoring location; (b) change in patterns recorded on 19/11/2018. *Source*: Aquafin NV.

The upstream pump logging clearly shows a sudden change in the duration of the pump cycle during dry weather. This is confirmed in the flow pattern at the downstream monitoring location. This example proves that the choice of locations should ideally take into account the potential interactions between different parts of the system.

The nature of the system (flat with fast surcharging or steep with mostly free-flowing conditions) defines whether specific monitoring locations and measured hydraulic parameters should be focusing on both dry and wet weather verification or only one of them. In Flanders, most models should be verified from upstream to downstream using low flows and from downstream to upstream using levels in surcharged conditions. Very often velocity measurements appear to be missing in surcharged conditions whereas the model can prove that in reality they drop below detection limit. It is therefore important in such systems not to focus on just level and flows, but equally on velocity.

Another typical point for attention in dry weather is the potential unbalance between level and velocity where flows show a good correspondence. A backup monitor at a nearby location might be useful to determine whether the unbalance is a result of wrong roughness estimates or of local gradient deviations.

11.6.2.2 Precipitation

For standard flow campaigns at Aquafin, at least two or three precipitation monitoring locations are selected, depending on the density of urbanization (usually one per residential area). As these short-term campaigns are usually carried out by a contractor, roofs of public buildings are preferred installation sites. For the project presented here the size of the studied catchment resulted in 12 tipping bucket rain gauges. These are preferred over more expensive options as the loss in accuracy is deemed acceptable and allows for a higher number of monitoring locations. The devices are installed on the ground on fenced company facilities (e.g. wastewater treatment facilities, pumping stations or storage tanks) as they are maintained by in-house personnel. To select appropriate locations, all available fenced sites in the project area have been assessed for the distance of the mounting point to the site fence (vandalism!) and any obstructions and GPRS signal strength. All sites deemed suitable after this test were geographically mapped and final locations were selected based on their coverage of the study area through Thiessen polygonization. If multiple sites remained as candidates in close proximity to an optimal monitoring location, preference was given to sites that would also host other monitoring equipment to optimize maintenance schedules.

11.6.3 Data communication

Flow data are manually transferred to an external data server on a weekly basis (service provided by the contractor) and downloaded from there. For all other data sources, data acquisition is done wherever possible in real-time or at different frequency intervals (10 min … 1 day) depending on the type of device used and preferably via wireless machine-to-machine (M2M) communication via public cell phone networks (GPRS, 3G). This is also true for devices recording data of pumping stations that are equipped with an Ethernet connection to the local SCADA system: company-internal security guidelines prohibit the installation of uncertified devices in such production environments.

As the project area is situated close to country borders, the use of SIM cards with enabled roaming was planned, tests for actual improvement of signal strength are still ongoing. For all locations not requiring data roaming, virtual-private-network SIM cards have been used to allow for high data security paired with ease of use in a fixed IP address (Internet Protocol address) range (no firewall issues). Data loss due to failed communication was limited to $<1\%$ as a result of sufficiently large data storage in the loggers, timely manual intervention and the use of high-performance antennae where required.

The different types of monitoring devices are reflected in different ways for data communication and had to be accounted for in the data import routines for the individual sensor types. Communication is carried out either as a push or pull service, directly to the sensor or via a sensor specific data server in the form of files or API (application programming interface) calls by a number of device-specific Matlab™ scripts. Sensors offering neither of these data acquisition methods or requiring manual intervention for data read-out have not been considered for use in the project presented here (except these handled by the flow survey contractor).

11.6.4 Data management, validation and accessibility

The data management system is designed around a three-level hierarchy of monitoring site (location or mounting place), monitoring device, and data channel (a time series of any variable, e.g. flow or pump switch-on level). To accommodate this structure, the system has been designed in-house as part of the project presented here. As the structure and performance of the system have proved satisfactory, the system will be used for future projects. All data are stored in one central relational *PostgreSQL*™ database (http://www.postgresql.org, accessed 28 April 2021) running on a company-wide accessible dedicated virtual server. The decision for *PostgreSQL*™ was based on the ease of use of vectorized time series data (data with multiple measurements per timestamp) as they are frequently used for spectrometric water quality measurements.

A history is kept for all channels connected to a device and all devices located at a site. This way, the user can transparently select, e.g. a full time series of the water level monitored at a certain monitoring site even though the initially installed device has been replaced after some time. As the data are still recorded per device, rather than per site, the user can also analyse monitoring data for individual devices (or channels) allowing to e.g. trace back device-dependent calibration errors.

Currently, only a basic automatized data validation (handling of broken data files, erroneous data due to interrupted communication) and unit and daylight saving time (DST) conversion is implemented, subject to extension over time. After data import, additional calculated channels such as corrected rainfall or Poleni based spill flow are determined. Formulae required for these calculations are defined in the channel's meta-data, to allow for easy modification.

All time series and meta-data can be consulted and manipulated by a feature-rich and flexible querying tool and free programming based on Matlab™. This tool also allows the import, visualization and analysis of frequently used data from external sources such as historians (e.g. GE Historian™), web-based data servers (e.g. waterinfo.be) and simulation results (here e.g. from Infoworks ICM™, SWMM (Storm Water Management Model). Alternatively, a read-only web interface exists for quickly creating views of time series data and a real-time overview on monitoring performance and device connectivity in a GIS-enabled, browser-based environment implemented as overlays on Openstreetmap™ (Figure 11.12).

Time series data are dynamically queried using PHP (Hyper text Pre-processor, also known as Personal Home Pages) and visualized with an existing JavaScript charting library (http://dygraphs.com/, accessed 28 April 2021).

The fairly detailed and expansible data structure for meta-data is inspired by DWA-M 151 (DWA, 2014) and is aimed at rendering the database self-explanatory to users not accustomed to the project itself. For example, all monitoring locations can be visualized in Google Streetview™ through a link, allowing easy recognition of the location when on site.

Each monitoring channel, device and site is assigned a state calculated in real-time which reflects the fitness of the data it represents: the data logger shown in Figure 11.12(b) occurs in red (intervention required) as the database did not receive any data for one of its channels (Pump 5).

Daily backups of the entire database ensure it can be restored in case of irreparable data loss or damage.

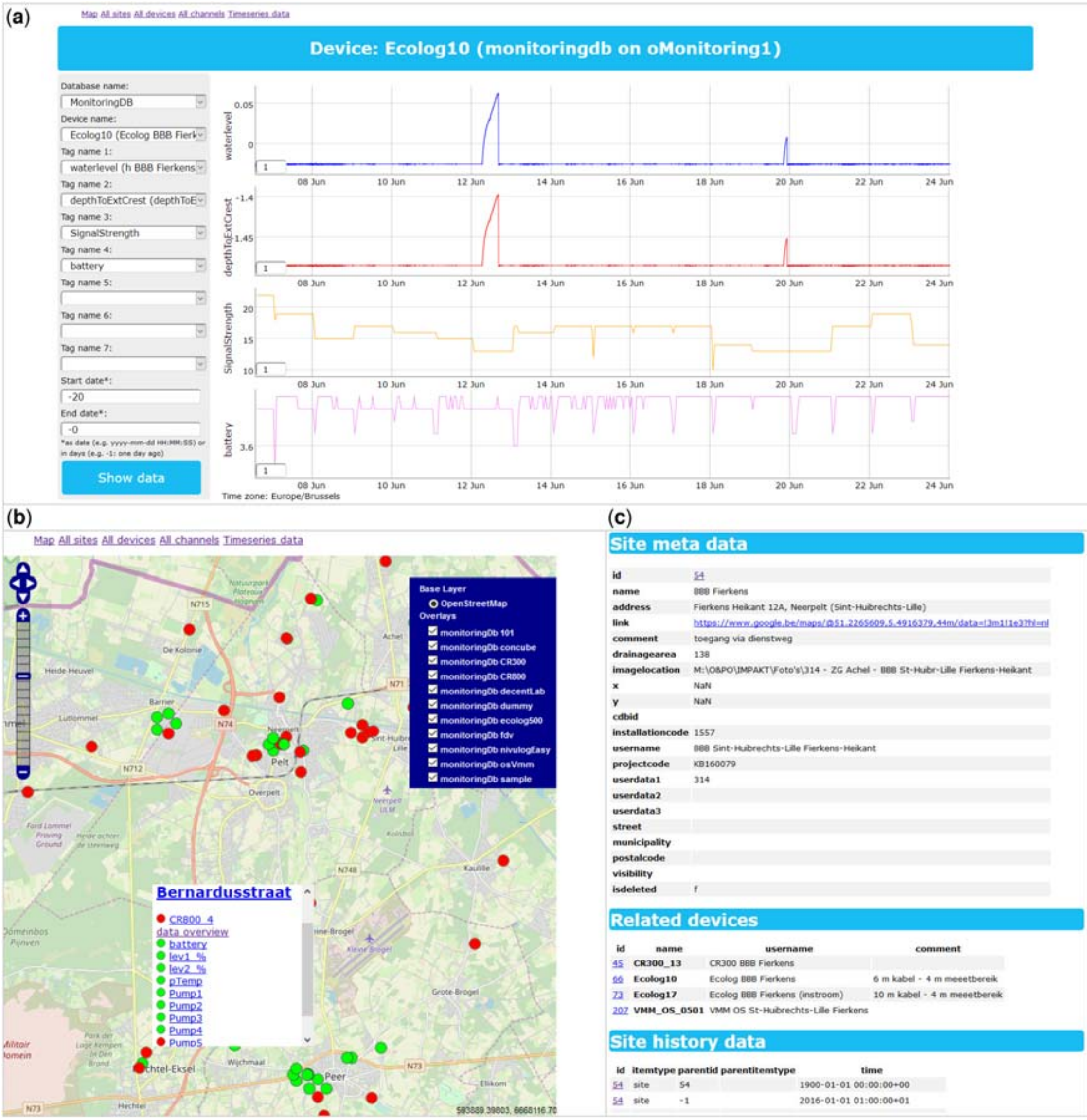

Figure 11.12 In-house browser-based real-time overviews on monitoring data; (a) time series data of three raw data channels and one calculated channel 'depthToCrest'; (b) map of sensor locations for monitoring performance and connectivity; (c) meta-data for one monitoring site. *Source*: Aquafin NV.

11.6.5 Sensor operation, maintenance and budget

11.6.5.1 Operation and maintenance

All monitoring read-outs are visually inspected at least weekly by the personnel who will later be working with the data, e.g. for model calibration to ensure sufficient data quality and plausibility. Implausible data, high noise ratio or comparable phenomena potentially caused by poor monitoring quality will lead to device inspection. Sensor maintenance is therefore accounted for in the weekly planning of technicians to ensure short response times.

All flow sensors are visually inspected on a weekly basis and calibrated under lab conditions once every year. Batteries are changed, if required. Water velocity and level are manually measured on site using a hand-held screw current meter and folding rule, respectively. Small corrections are possible on-site, large deviations will lead to sensor replacement. If necessary, the wetted section will be re-surveyed. In the case of doubtful results for flow, water level and especially velocity measurements can still lead to important insights into system characteristics and are used for data verification. For intervals of ambiguous flow data, at the very least a cross-comparison of level and velocity is carried out.

Pressure gauges for water level monitoring typically receive no regular maintenance. If a drift is noted in the data, the sensor is cleaned and carefully re-installed to its exact position in the location. In-house rain gauges are cleaned when personnel are on-site and if necessary. Rain gauges maintained by the contractor are inspected and cleaned on a weekly basis.

Sensors that work on non-rechargeable batteries require regular and in-time replacement of the batteries (lifetime varies depending on many parameters). Therefore, preference is given to equipment and locations that have power supply (e.g. pumping stations). The level sensors chosen for this project required battery replacement roughly every 3–4 months.

11.6.5.2 Budget and cost considerations

Only rough estimates of CAPEX (capital expenditure) and OPEX (operating expenditure) can be given in Table 11.5, all listed costs are excl. VAT.

11.6.6 Challenges and lessons learnt

11.6.6.1 Planning

Desirable monitoring locations are not always suitable locations: during this project, a sensor installed in the influent channel of one of the WWTPs led to an increased risk of clogging. This provoked flooding of the (unmanned) installation (Figure 11.13). This could have had the same effect anywhere in the sewer system: flooding caused by monitoring!

Table 11.5 CAPEX and OPEX estimates for monitoring equipment and maintenance.

	CAPEX	OPEX
Flow survey contract		80,000 €/year for 10 sites, weekly maintenance
Rain gauge	2500 € pp (incl. logger, modem)	
Water level sensor	1500 € pp (incl. logger, modem) 75 € pp (replacement battery)	25 person days per year for 20 devices, mostly for battery change, incl. some re-configuration
Data logger for pumping stations	1000 € pp (including modem)	20 person days for 25 locations, mostly modem re-sets, incl. cleaning of rain gauges
M2M SIM cards		5 €/month/device in a bundle within a company-wide contract with the network provider

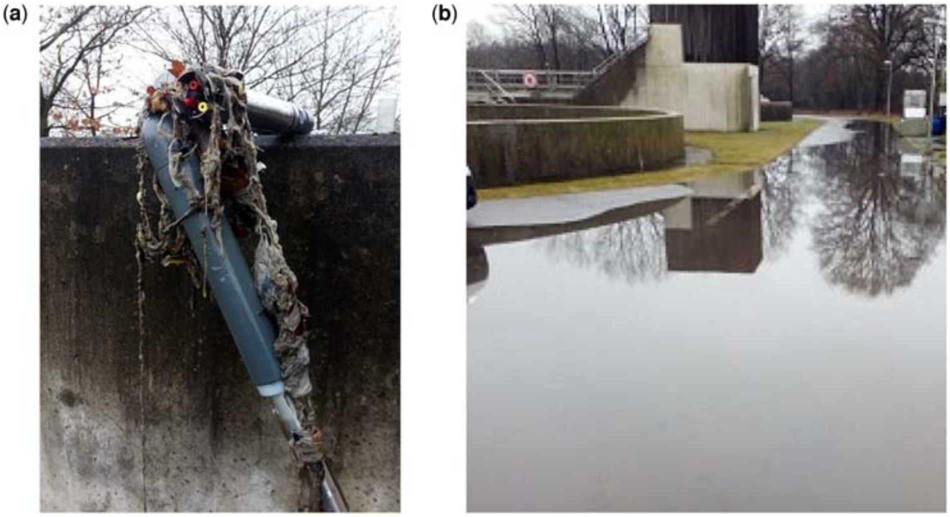

Figure 11.13 Flooding caused by monitoring; (a) monitoring device and accumulated debris after removal; (b) resulting flooding throughout the WWTP. *Source*: Aquafin NV.

Even though desk studies are valuable and frequently deemed the most significant source for the identification of optimal monitoring locations, the value of experience of operational staff and maintenance technicians cannot be rated highly enough, for systems characteristics as well as sensor installation. These personnel should be involved in the planning of the monitoring campaign as early as possible.

While the traffic situation at monitoring locations can play a major role, another important aspect is the accessibility of monitoring locations. This is especially true for public parking lots, where parking prohibition (depending on regional law) cannot be granted for the full period of the monitoring campaign. Temporal parking prohibition for regular intervention can then lead to significant administrative overheads making the choice of a different monitoring location preferable.

The installation of monitoring equipment under sealed manhole covers should be avoided. Most devices – even when tested for IP code 68 – are only water resistant for a limited amount of time.

Installations at locations with high turbulences in the conduit should be avoided for flow monitoring. Ideal locations are the incoming conduits of manholes with one single ingoing and one single outgoing pipe in line with one another and no nearby invert steps. Installation of flow meters directly in manholes is to be avoided to prevent the interference of debris accumulating in the manhole.

Preferably, flow sensors should be installed at locations without sedimentation. If this is impossible, locations with firm sediment layers should be preferred over locations with soft sediment, to prevent sediment accumulation on the sensor. While the installation of flow sensors outside the centre of the sewer invert is possible using an offset configuration, it can lead to less accurate results, possibly to asymmetric velocity patterns in the wetted section.

For flow measurements in conduits with large and complex cross-sections it can be beneficial to work with two sensors simultaneously to increase the accuracy of average velocity measurements. Most devices support this without requiring additional post-processing of the monitoring data for the user.

The installation of monitoring equipment in close vicinity to high-voltage cables should be avoided as the electromagnetic field can – in rare cases – influence sensor performance and wireless communication.

Especially when using legacy devices, flow meters should be installed in conduits with standard shapes, if possible, as the configuration of user defined profiles can be tedious and error prone.

One frequently employed way of installing flow monitors in sewer pipes is through the use of mounting rings built from metal plates that can be installed in the pipe without the need for mounting holes in the pipe walls. While this is the only way of installing a flow measurement in re-lined conduits (where drilling holes into the pipe walls is not an option), at all other locations, the flow meter should be directly mounted to the conduit wall as mounting rings might untighten, especially in harsh hydraulic conditions and at locations prone to sedimentation.

11.6.6.2 Data communication

Real-time (or close to real-time) availability of data is commonplace for almost all types of sensors and can be considered the most important pre-requisite for efficient sensor maintenance. It should be insisted on for all new devices if sensor purchases are envisaged. Download intervals should be chosen as a compromise of urgency for plausibility checks and data validation (and resulting counter measures) and battery lifetime. Data security considerations can make it necessary to rely on GPRS connections for data acquisition even at locations were wired communication is available.

While the adoption of standardized protocols for data communication should be encouraged for new devices, the use of legacy devices will make it necessary to design an extensible, flexible system, which can handle arbitrary (future) data formats.

11.6.6.3 Operational aspects including data management

Flexible plastic tubing, as used for the protection of network or electricity cables in building constructions, can be applied for additional protection of cables subject to in-sewer installations. They then serve as an effective prevention measure of sharp bends in the pressure compensation lines of pressure gauges.

Responsibility – sensor stewardship: for each device there should be a contact person, a staff member who knows where and why the sensor was installed, and what its typical mode of operation is. Ideally, this person will later have to work with the sensor data to ensure a natural interest in the quality of these data resulting in frequent (≤weekly) plausibility checks and – if required – maintenance.

Data that cannot be placed in the correct context are of little value. The use of meta-data should thus be enforced wherever possible. This can be easily realized by the sensor network administrator by only allowing sensors to be added into the monitoring system if a minimum amount of meta-data (e.g. proper naming, address or X-Y-coordinates of installation site) are provided so that the monitored signals are self-explanatory to colleagues and project partners.

Aside from flexible data analysis tools, also low-threshold, ubiquitous access to the data should be provided to ensure project-wide adoption. The usability of the web interface (initially purely conceived for maintenance personnel) of the project presented here has led to other projects migrating their data into this database purely for its ease of data access.

For any monitoring campaign that accommodates multiple sensors for more than a couple of weeks, the use of an adequate database architecture should be preferred over data storage in individual files: the amount of data currently maintained in the database (80 GB as of July 2020, after 3.5 years of operation) would be challenging when using files but is inconsequential when using database systems. Once a suitable database system is established, it can easily be extended to allow for the connection of new sensors and device types. This, in turn, will lead to increased acceptance of the system over time and ultimately allow for more professional and sustainable data handling and create a platform for the accumulation of knowledge and experience with respect to monitoring campaigns.

Data backup (for time series and meta-data) will become relevant at some point in every monitoring project. Proper data backup and restoration procedures should be in place and regularly tested (a copy of time series data into a spreadsheet/text file is no backup!).

Company-/project-wide communication and operator involvement are of the utmost importance for good operation: sensor data that are visible to the operating staff in real-time, and help explaining system characteristics, will be cared for. The inverse is true also.

The currently used sensor network and data management and storage system(s) is/are never complete. Easy integration of external data from other platforms or files and future monitoring campaigns should be anticipated.

11.7 'NEXTGEN' URBAN WATER MONITORING – A HIGHLY DISTRIBUTED FIELD MONITORING OF URBAN DRAINAGE NETWORK WITH AFFORDABLE SENSORS AND REAL-TIME DATA COMMUNICATION, AUSTRALIA

11.7.1 Scope and objectives

In conventional urban water monitoring, a sampling station is usually established at the catchment outlet to measure the flow and to analyse pollution levels. Researchers relied on data collected at this single point to develop models and design mitigation strategies, however, most of them end up with a poor model performance (Bonhomme & Petrucci, 2017; Dotto *et al.*, 2010). One of the main reasons for this is that by lumping the study area into a simple system, researchers ignored the inconsistency (e.g. land uses and randomly-occurring dry weather discharges) happening at the site-specific level within the catchment. To overcome these, the NextGen Urban Water Monitoring is a long-term data collection approach aiming at providing real-time information about flow and water quality in urban catchments at high spatiotemporal resolution (i.e. depends on the monitoring purpose – usually at the street or lot scale).

The high cost of installing multiple conventional sampling stations (>AU$ 12,000 ~ € 7,300) for a flowmeter and autosampler) in an urban catchment hinders data collection at a higher spatial resolution. Making the sensor and data transmission affordable but also providing reliable readings have become the top priority of NextGen monitoring initiatives. From the pollution source tracking perspective, the proposed sensor and data logger must be smaller than conventional sampling techniques which do not require any surface assets. In addition, the sensor must be easy to install and relocate within a catchment, i.e. avoiding any confined space entry within the catchment to minimize the budget and time to do one installation.

Based on the fundamental requirements of NextGen Urban Water Monitoring, this project was inspired by the recent development and innovation of Arduino and Arduino-compatible hardware components. The proposed Arduino data logger with 3G shield, 7.2 V battery, depth and EC sensors (Figure 11.14) were tested under lab and field conditions and eventually installed in a study catchment to track the highly polluted discharge area. The installed Arduino loggers with telemetry functionality continuously upload live data to a development website for data adjustment (e.g. calculating water depth and EC from raw data) and storage (Figure 11.14). Based on pre-set triggers, alarms will be sent to corresponding persons via SMS, which allows an immediate inspection when unusual discharges appear during a dry weather period. The collected spatiotemporal dataset can also generate an FDI (fault detection and isolation) database which characterizes the appearance frequency, flow duration and intensity of various land uses and urban activities. Such a database allows researchers to consider the impact of non-rainfall driven pollution sources in urban water models.

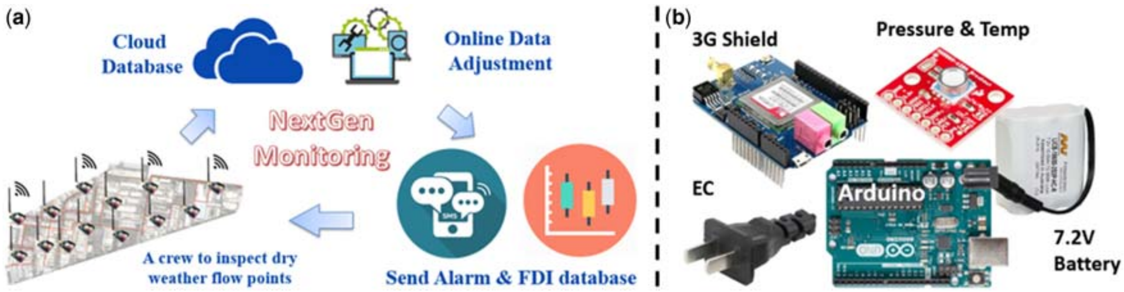

Figure 11.14 (a) data collection process of NextGen Urban Water Monitoring network; (b) Arduino logger package including cheap US power cable, 3G shield, MS5803 pressure sensor and 7.2 V battery. *Source*: EPHM Lab and BoSL.

11.7.2 Measured variables

11.7.2.1 Water depth measurement

The water depth of stormwater flow is measured by a high resolution and low power altimeter sensor – MS5803-01BA from TE Connectivity. As MS5803 measures the absolute environment pressure, another sensor needs to be installed in the catchment surface to correct for air pressure changes and temperature for density changes. A 3D printed sensor case was designed for easy installation in the urban drainage network. A potting compound gel was utilized to fill the sensor case, which ensures all the electrical connections and the sensor itself will be waterproofed under 3 m of water.

To verify the accuracy of the Arduino depth sensor MS5803, we installed one Arduino sensor adjacent to a HACH submerged probe inside a stormwater drain (Figure 11.15(a)). At this specific sampling location,

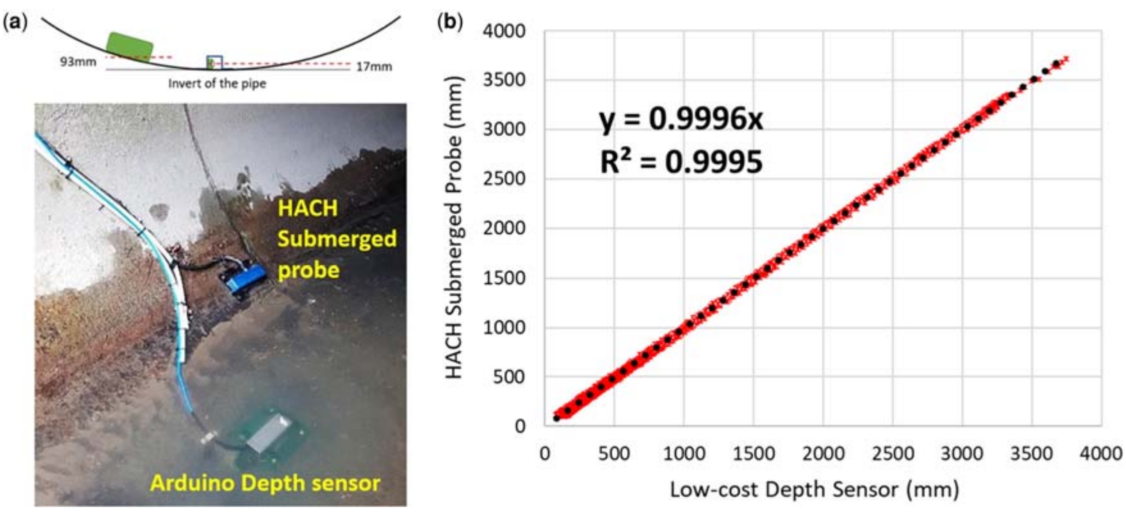

Figure 11.15 Arduino and HACH sensors installation location inside an urban stormwater drain; (a) The water level readings of a rain event; (b) Correlation between Arduino and HACH sensors. *Source*: EPHM Lab and BoSL.

although the pipe diameter is only 1.8 m, the water level could go up to 3.8 m and become the overland flow of a creek. The HACH sensor was installed towards the side of the pipe due to the high sediment accumulation, which always buries the sensor, thereby affecting the level and velocity readings. The comparison between the low-cost Arduino depth sensor and the HACH submerged probe over a one-month deployment (Figure 11.15(b)) shows a linear correlation, which indicates that the low-cost sensor is capable of measuring the water level as accurately as high-end products.

11.7.3 Study catchment, location of monitors and installation methods

In order to verify the performance of NextGen Urban Water Monitoring system for detecting urban dry weather discharges, more than 20 Arduino-based loggers have been installed in stormwater drains of Old Joes Creek catchment (Figure 11.16). Old Joes Creek is a suburban catchment with mixed industrial and residential land uses towards the east of Melbourne with a total catchment area of 854 ha. The red-shaded area is a 200 ha industrialized region close to the catchment outlet, which has been recognized as the major pollution contribution of the downstream waterways. Hence, 17 Arduino loggers are installed inside the industrial area mainly to capture the discharge events. A few sensor modules are also installed outside the area to capture different commercial activities like the shopping precinct, local community centre and even residential input.

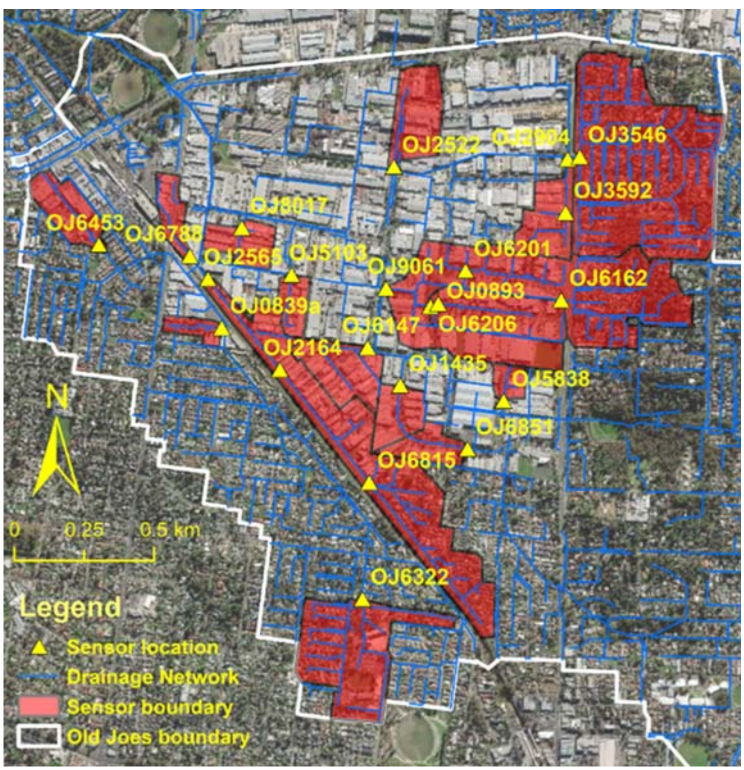

Figure 11.16 NextGen Urban Water Monitoring system in Old Joes Creek – locations of installed monitors, catchment boundary and drainage networks. *Source*: EPHM Lab and BoSL.

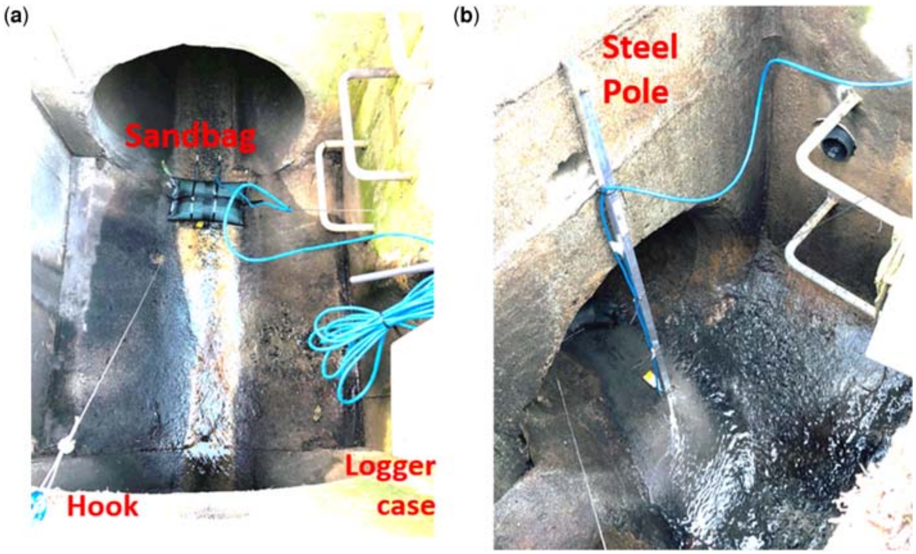

Figure 11.17 Typical installation methods of NextGen Urban Water Monitoring sensors in drainage network – attaching to a sandbag (a), fixing a pole with anchors and connecting the sensor to the bottom of the pole (b). *Source*: EPHM Lab and BoSL.

To minimize the installation time of one sensor module and make it easy to maintain and relocate, confined space entry into stormwater drains is not permitted in this project. Two installation methods were trialled in this study: attaching the sensor to a sandbag or fixing the sensor to a steel pole (Figure 11.17).

The sandbag is used to keep the sensor in the right position and prevent it being washed away during the wet weather event. Two stainless steel ropes are attached to the front corners of the sandbag, and the other ends are attached to installed hooks closed to the pit lid. The significant advantage of the sandbag method is the quick installation – usually, it takes 30 minutes to install one sensor. However, the research team has also experienced two major issues: (i) sandbag can easily flip over after a large rain event, leaving the sensor on top of the sandbag (in the air) and detecting nothing; (ii) the sandbag will create a pool of water, which is acceptable when we only want to know whether there is flow coming down from the upstream, but means it is not possible to record the true water level.

As an enhanced option, a steel or aluminium pole has been used to hold the sensor at a fixed location, without requiring a worker to enter the drain. This installation method has been trialled at 10 sampling sites, which all showed reliable sensor readings over a sampling period longer than 3 months. The sandbag is not required in this method anymore, so the measured water level will not be affected by pooling water. During the field trial of this installation method, the only issue is that the installed pole tends to capture leaves and other plastic rubbish, and so requires regular manual cleaning. The research team was worried the stick might be bent during a rain event, but it was strong enough to even hold the sensor in the right place under two major flood events where the stormwater overflowed the pit. In conclusion, the steel/aluminium pole method will be the standard method of installation for future urban drainage network monitoring projects. The low-cost sensor is also easy to install for other water assets such as the wetland and biofilter.

Table 11.6 Detailed costs of Arduino-based sensor of NextGen urban water monitoring.

	Components	Cost (AU$)
1	Tosduino Uno R3	16.00 (€ 9.5)
2	SIM5320 Shield	70.00 (€ 42)
3	MS5803−01BA Module	28.00 (€ 16.8)
4	Waterproofed box	2.60 (€ 1.70)
5	Cables and connection glands	6.00 (€ 3.60)
6	Marine epoxy and araldite	10.00 (€ 6)
7	7.2 V lithium battery 9500mAh	105.00 (€ 63)
8	SIM card	5.00 (€ 3)
Total		242.60 (€ 145.5)

11.7.4 Sensor cost and maintenance

The net present value of one Arduino-based monitoring module is approximately AU$ 242.6 (€ 145.5). The detailed cost of individual parts is listed in Table 11.6. The lithium battery and SIM5320 shield for 3G connection are the two most expensive parts, which account for 72% of the total cost of one module. The cost of the steel or aluminium pole is slightly variable per site depending on the depth of the manhole.

Currently, the sensor network maintenance including sensor checking, re-calibration, re-installation, battery changing and site cleaning runs on a bi-weekly basis which takes a full day of 8 hours of two employees. With increased numbers of sensors being installed in the catchment, the cost and time taken for network maintenance may further increase. In order to minimize the maintenance cost, apart from achieving a stable performance of the sensor network (i.e. minimize sensor malfunction), the power consumption of the current Arduino-logger should be further reduced to make the sensor run for longer than three weeks. Our newly developed Arduino-compatible module (in testing) is aiming to have a lifetime of more than half a year by minimizing unnecessary functionalities of the existing Arduino and 4G internet connection technology.

11.7.5 Data storage and website management

The data collected in this case study are stored in the web-based cloud of the Enhancing our Dandenong Creek project (EoDC, http://www.eodc.com.au, accessed 28 April 2021). The website is designed and maintained by BoSL of Monash University, Australia (http://www.bosl.com.au, accessed 28 April 2021, for further information about our recent low-cost sensor technology development). The EoDC project website has the following key functions and features:

- Stores raw data that uploaded from each deployed sensor.
- Automatically runs scripts to clean the data (data quality check and removal of poor quality data).
- Automatically backs up all data, twice daily by sending to the correspond manager's email address.
- Collects rainfall data based on the sensor location and the radar image from Bureau of Meteorology, Australia.
- An alarm system which sends SMS to the corresponding person when improper stormwater discharge is detected.

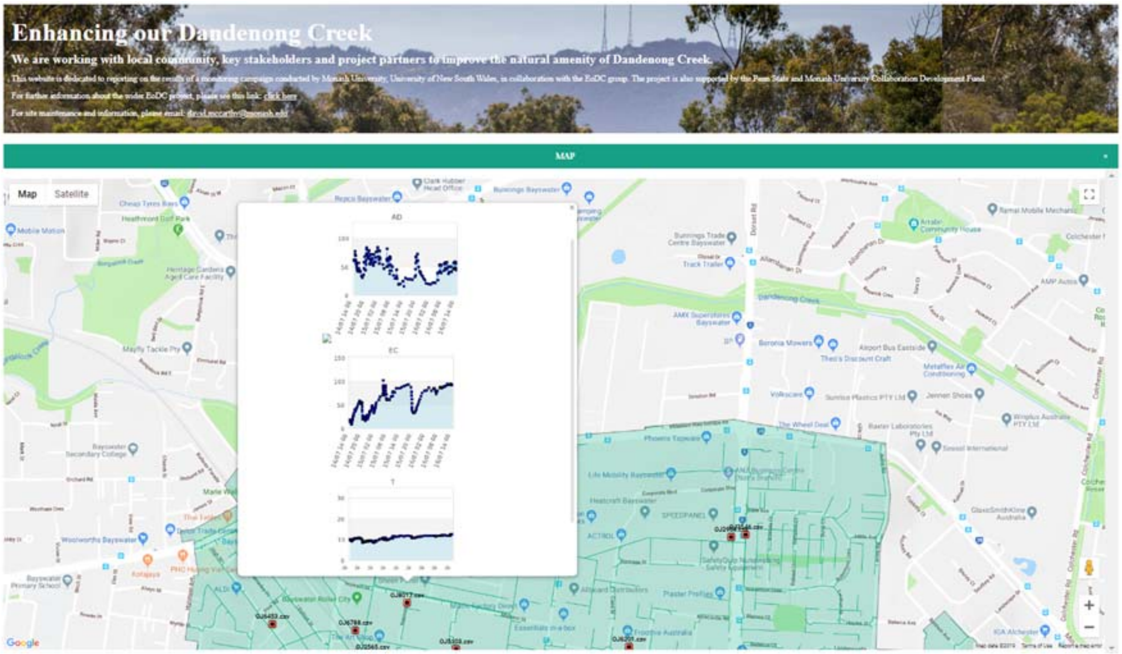

Figure 11.18 Web-based platform of NextGen Urban Water Monitoring – EoDC project. *Source*: Google Maps, EPHM Lab and BoSL.

In the current website of the EoDC project (see Figure 11.18), catchment boundaries, drainage network and sensor locations are marked on top of the Google Map. By clicking each site, live water depth, temperature and EC data are directly plotted for users to check the trend over last 48 hours. A raw-data (in csv format) download link is provided at the bottom of the pop-up window. The cleaned data are only accessible through the website's backstage database.

11.7.6 Data quality check, cleaning, and validation

The raw data collected from the low-cost sensor need to be cleaned and validated to remove all poor-quality readings (e.g. negative readings due to sensor malfunction). A data checking algorithm is used to automatically create a cleaned data file. By checking each scan in the time series data, the algorithm can assign different error codes based on the following criteria and possible data issues:

- Abnormal water pressure readings (water level <-0.5 m or >5 m, based on individual case study's condition).
- Unusual temperature readings (<-5°C or >40°C).
- No reference air pressure readings within one-hour time.
- When the sensor is under maintenance.

A meta-data file will be automatically created for each sensor site at the same time the sensor is being cleaned. The meta-data includes the description of each error code, how many poor-quality data points are detected under each error code, and when these errors occur in the time series.

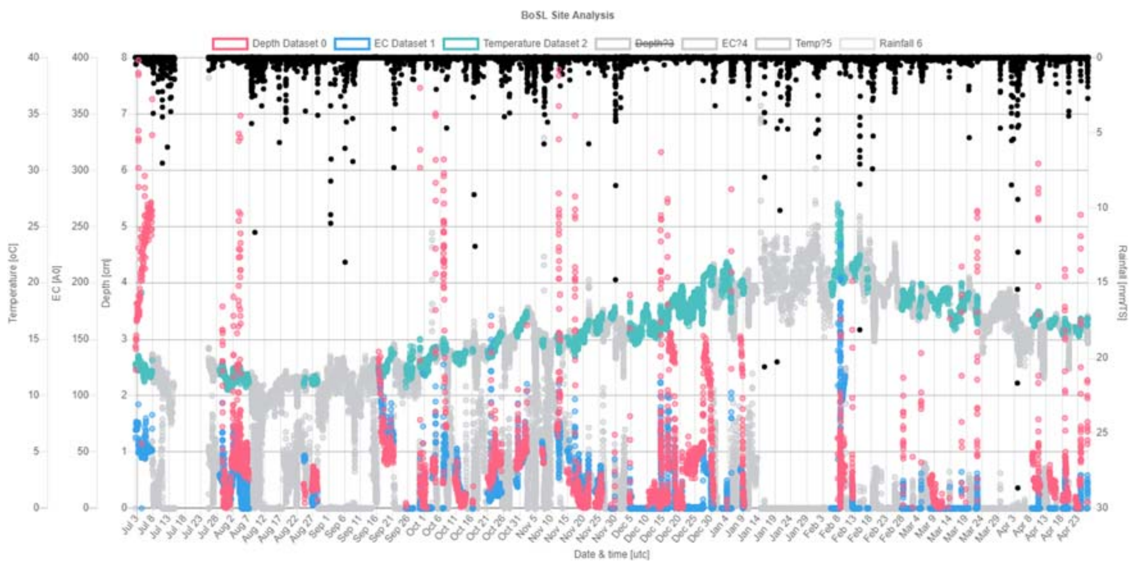

Figure 11.19 Time series plot of the clean, validated and dry weather data for one of the sensors in this case study; poor quality data or wet weather periods are greyed out in this figure; red – depth readings, blue – conductivity readings and green – temperature readings. *Source:* EPHM Lab and BoSL.

Apart from cleaning the poor-quality data, the data checking algorithm is also designed to correct the potential depth sensor drift by using the sensor recalibration results collected during each manual site maintenance. In addition, the actual weather condition of each data point (either wet or dry) is determined based on the rainfall intensity data collected from radar imageries every five minutes. When the cumulative rainfall during the previous 6 hours is more than 1 mm, the data are considered in a wet period and will then remain to be considered in a wet period for the next 48 hours.

The final cleaned data are automatically plotted on EoDC website's data analysis portal (Figure 11.19 – under testing and not available to the public). This plot includes water depth, EC, temperature, and rainfall data collected during the sampling period. Users can zoom in and out to check the data of a specific period of their interest. The poor-quality data are automatically greyed out, and the users can click onto the legend bar to turn off the data they are not interested in (e.g. data collected during wet weather period).

11.8 THE UWO – A FIELD LABORATORY FOR DISTRIBUTED REAL-TIME MONITORING WITH LOW-POWER SENSOR AND DATA COMMUNICATION TECHNOLOGY, FEHRALTORF, SWITZERLAND

11.8.1 Scope and objectives

The Urban Water Observatory (UWO, http://www.eawag.ch/uwo, accessed 28 April 2021) is a dedicated long-term monitoring initiative aiming at (i) collecting a consistent dataset on water and matter fluxes in an urban area at very high spatiotemporal resolution (1 sensor / ha; 5-minute recording interval), and (ii) testing and developing a low-power sensor and data communication technologies for efficient environmental and infrastructure monitoring. The UWO field laboratory was commissioned in early 2016, and it is expected to run at least until the end 2021. At the time of writing (i.e. 2020), the UWO sensor network consisted of more than 120 different sensors, deployed across various compartments of the urban water cycle. Besides typical urban hydrology parameters such as precipitation, water level and flow, data on (waste-)water temperature and conductivity (i.e. capacitive sensors, inductive conductivity) were collected in sewers, in rivers, and in the groundwater compartment.

The project was inspired at a time at which miniaturization of hardware components, increasing computational capacities and the integration of various types of digital technology in our everyday life became more and more prevalent, and this digital transformation started to expand into the urban water sector. A key objective was to illustrate benefits and limitations of a so far unseen sensor density in the context of distributed, long-term, real-time urban drainage monitoring. Furthermore, pressing challenges like an increasing regional water scarcity, increasing flood risk due to a changing climate, and a growing cost-pressure for operation and maintenance (for instance due to high sewer infiltration rates), motivated the establishment of the field laboratory in the municipality of Fehraltorf, Switzerland (Figure 11.20).

Essentially, the project attempts to collect consistent data for water research, and to coherently study, field-test and advance four interrelated aspects in the process of data collection (Figure 11.21): 1–sensor application, 2–data communication, 3–data management, 4–semi-automated data validation.

Common to most urban drainage monitoring initiatives are: (i) often a considerable effort for installation in underground locations that are difficult to access and explosion endangered increasing maintenance intervals (associated with costs), and (ii) a limited scalability and flexibility in terms of deployment and operation. Hence, the following operational requirements can be formulated:

- A cheap, reliable and scalable wireless communication enabling data collection in real-time.
- A solid energy supply for sensor and transmission technology with long battery lifetime up to several years.

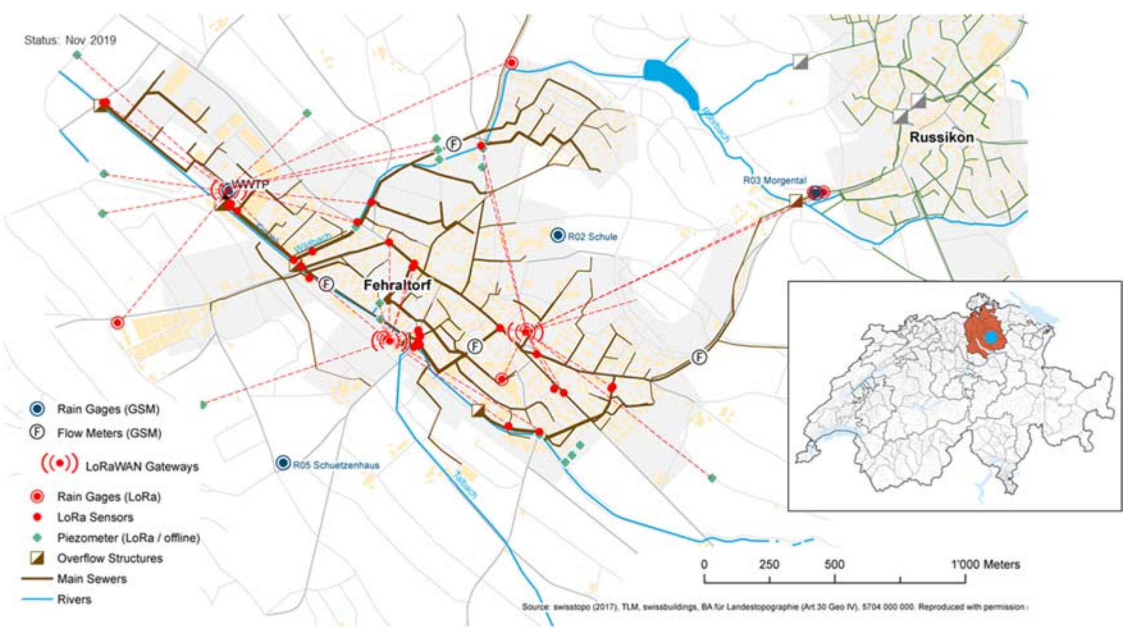

Figure 11.20 Overview on the UWO sensor network in Fehraltorf including sensors and low-power wide-area network (LPWAN) infrastructure (Status: November 2019). Small figure: location of the Canton Zurich and the case study location, 12 km north-east of the city of Zurich within Switzerland. *Source:* Eawag.

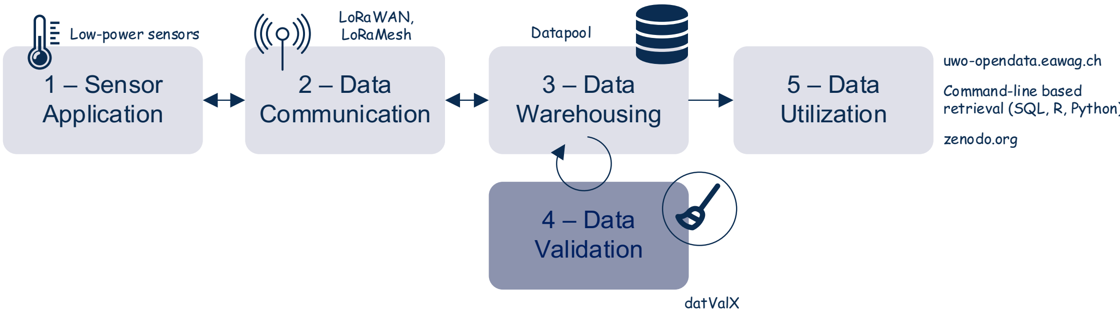

Figure 11.21 Principal understanding of data collection as a coherent process, including individual contributing components, i.e. projects embedded within the UWO initiative. *Source*: Blumensaat *et al.* (2018).

- A simple and fast installation without structural modifications of sewer infrastructure, such as the removal of antenna cables or the installation of special radio-enabled manhole covers.
- Fully time-synchronous sensor readings.
- A high standard regarding data encryption and security.
- Sparse, flexible and non-proprietary data management solution.
- Devices that are suitable for use in explosion-proof environments, solely due to their hardware components.

These particular aspects motivated the UWO research, which eventually lead to the development of the following components for a 'From-the-Sensor-Signal-to-the-Data-Point' pipeline (Figure 11.21):

- 1 – Low-cost and ultra-low-power sensors for CSO detection and wastewater characterization.
- 2 – A new wireless data communication protocol based on the LoRa technology (Ebi *et al.*, 2019), fully compatible with the renowned LoRaWAN (long range wide-area network) standard (LoRaWAN, 2015) to overcome range critical situations, as they occur when transmitting data from underground.
- 3 – A mature data warehouse application named Datapool (Blumensaat *et al.*, 2018) allowing for flexible integration of various data sources (own sensors, SCADA systems, meteorology services and foreign servers) from multiple data providers.
- 4 – An automated data validation pipeline (Disch & Blumensaat, 2019) enabling real-time data curation and timely sensor maintenance (datValX).

11.8.2 Catchment area, measured variables and location of monitors

11.8.2.1 Catchment area and operation challenges

The investigated urban catchment Fehraltorf (Figure 11.20) is a Swiss-typical settlement with a modified combined sewer network (13 km combined sewers, 4.6 km foul sewers, 10.9 km storm drains) where sanitary sewage and some stormwater flows are carried to a central wastewater treatment plant (WWTP; design capacity: 12,000 PE). A small proportion of the stormwater is directly discharged into receiving creeks without any treatment. The total settlement area adds up to 127.3 ha, however, only 40 ha can be accounted for as areas connected to the combined system. A significant share of the sewer pipes lies below the groundwater table. Thus, sewer infiltration is – depending on the season – considerable and contributes to the WWTP inflow with an estimated varying rate of 35% up to 55%. Sewer rehabilitation planning is ongoing but constrained by limited municipal budgets. Four sewer retention basins, adding up to an average specific storage volume of 36.1 m^3 per hectare runoff-efficient area, are implemented to mitigate impacts on the receiving waters. Excess flows are discharged via five main combined sewer overflow (CSO) structures into ecologically sensitive, partially baseflow-regulated receiving rivers; one quarter of the base flow in the River Luppmen is WWTP effluent (dilution ratio 3:1).

11.8.2.2 Sensor network evolution

Network architecture: The sensor network can be partitioned into two parts: (i) a 'monitoring backbone' consisting of four conventional rain gauges and seven high-precision flow monitors operated on batteries and equipped with cellular data loggers, and (ii) a low-power wireless sensor network (LPWSN) which – in 2020 – collected data from more than 90 low-power sensor nodes using wireless low-power communication, i.e. LoRa-based techniques. In 2020 we collected 123 monitoring signals covering the system dynamics at 1 to 5 min temporal resolution. This corresponds to more than 50,000 data points, i.e. sensor observations, per day, excluding operational parameters such as battery voltage. Data from rain gauges are collected in 1-minute intervals. Sensors are positioned according to the monitoring objectives, i.e. primarily across the central part of the drainage network, along the main collectors, and at overflow structures. Groundwater piezometers are established around the municipal area and next to main collectors. Many locations are equipped with two or more sensors of the same or different types to intentionally pursue the concept of signal redundancy and signal diversity. Sensor positioning is clearly motivated by aspects related to urban drainage and flow topology, but not necessarily related to an optimum wireless communication network coverage (see discussion below).

Rain gauge network: In total 14 rain gauges, 4 conventional (weighing principle; OTT Pluvio II L) and 10 low-power rain gauges (R.M. Young, Model No. 52203; LUFFT, WS700) are established in an urban area of 127.3 ha. This rain gauge density in particular allows the capture of spatial rainfall variability, e.g. during convective summer storm events. Rainfall data are used to feed hydraulic sewer models and to align with radar information provided by the Swiss National Weather Service. The seven low-power tipping bucket rain gauges have been found to be generally within a similar range of accuracy as the high-precision weighing gauges (<5%). Still, for extreme rainfall events, these rain gauges tend to underestimate rainfall depths (~15%). The gauge deployment revealed that the adequate positioning of rain gauges in urban areas is not trivial. Compliance with WMO standards, which do not specifically address requirements in urban areas, on the one hand, and finding operational solutions on the other hand, lead to compromise solutions.

Flow monitoring: In-sewer flow rates are monitored at four strategic locations, i.e. at main collectors within the network, at connecting sewers carrying transfer flows from adjacent settlements and at the inlet of the central WWTP. Three of the four locations are equipped with redundant flow sensors but of different monitoring principle (radar and US Doppler techniques; Nivus, Flodar, Sommer).

11.8.2.3 Low-power wireless sensor network

A key component of the UWO is a fully scalable, low-power wide-area network (LPWAN) communication system, consisting of sensor nodes and gateways. This concept is based upon the new, yet renowned standard LoRaWAN™ allowing for a bidirectional radio communication link between battery-driven sensor nodes and central gateways over a long range (~10 km, for above ground applications).

Whereas other LPWAN techniques exist (Raza *et al.*, 2017), LoRaWAN was chosen for three main reasons: (i) low-power data transmission on a license-free bandwidth, in Europe 868 MHz, (ii) a standard with an open-source-like character with a growing community of developers and users, and (iii) availability in 2015, when the UWO was initiated. The LoRaWAN architecture is laid out in a star-type

Figure 11.22 Hardware components in LoRaWAN sensor node prototype, embedded in an ATEX compatible chassis. *Source*: Eawag.

network topology, i.e. each individual sensor node directly communicates with the best available gateway through a contention-based approach, meaning that data are sent without receiving acknowledgement messages. In the case of the UWO, three 'privately' operated gateways (Kerlink, Wirnet Station 868), one solar-powered and two AC-powered, currently collect data from more than 90 low-power sensors (Figure 11.22 – status: November 2019).

Battery-powered sensor nodes, i.e. LoRa-enabled loggers which various sensor types can be connected to, are (i) self-designed and -manufactured prototypes (Figure 11.23), and (ii) manufactured by an external supplier (http://www.eawag.ch/uwo, accessed 28 April 2021) according to our design specifications.

Figure 11.23 LoRaWAN prototype including water level sensor (MaxBotix) installed in a sewer manhole. *Source*: Eawag.

Currently, the following sensors are integrated into our LPWSN: 34 ultrasonic level sensors (MaxBotix MB7389, MB7369, MB7386), 10 dielectric conductivity sensors (Decagon, 5TM/5TE), 2 pressure gauges (Keller, 36 XKY), 15 multi-parameter probes for groundwater quantity and quality monitoring (*STS*, DL/N 70; Keller, 36XiW-CTD,DCX-22-CTD), 5 humidity sensors, 26 dual in-sewer temperature sensors (DS18B20), 1 very low-cost pluviometer (Davis), and 7 low-power tipping bucket rain gauges (R.M. Young, Model 52203).

11.8.3 Data management, validation, availability

11.8.3.1 Data management

Existing data management solutions are generally designed with a very specific work- and data-flow in mind – which is most unlikely to correspond exactly with your needs. So even while the underlying database platforms are commonly well-established, the full sensor data warehouse needs careful technical specification, a design concept and individual configuration. For the UWO we aimed at a solution that (i) can handle very diverse data (types) of potentially yet unknown sources and formats, (ii) stores and links data and meta-data simultaneously, (iii) ensures consistency of the data whenever possible, (iv) makes data usage at the front-end easy, and (v) does not require in-depth skills to add novel data sources. Note, the flexibility of point (i) limits the potential for automation and makes point (v) inevitably harder.

The result of our efforts is a data warehouse application named Datapool. This solution is based on separation of concerns: a field scientist (cf. data provider – see Figure 11.24) adding a new sensor is responsible for providing (i) a file with meta-data and (ii) a conversion script to transform raw files from the sensor into a standardized text format. As soon as a new raw file arrives from a sensor the Datapool applies the corresponding (conversion) script automatically and imports the data into a relational database (PostgreSQL). Finally, data users can either directly query data and meta-data, use packages (available in R, Python, Julia, Matlab) with a basic set of query functions, or use a web interface to

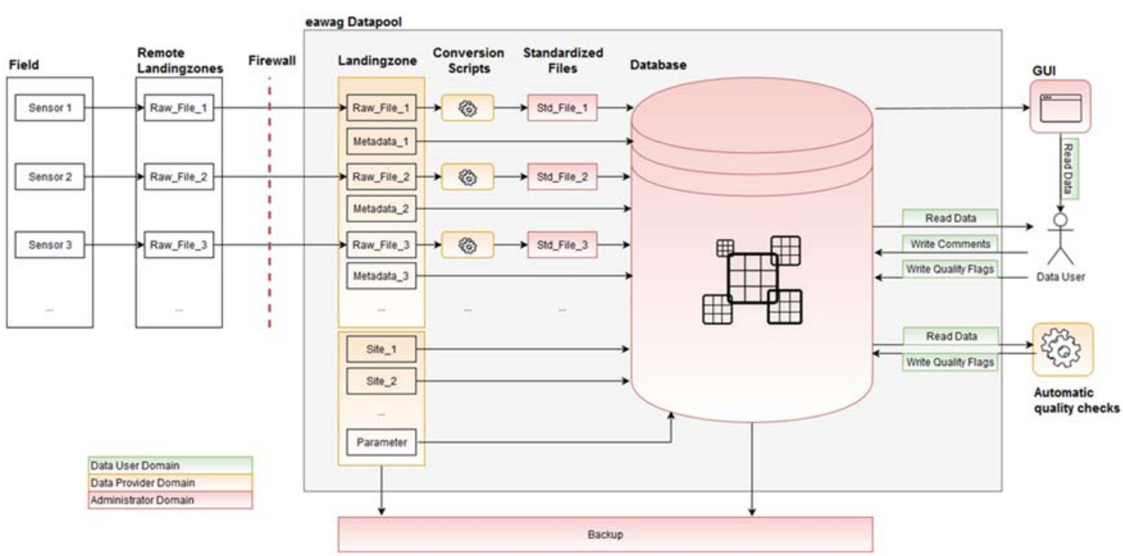

Figure 11.24 Concept of and data flow in the data warehouse application Datapool. *Source*: adapted from Blumensaat *et al*. (2018).

retrieve data (http://www.uwo-opendata.eawag.ch, accessed 28 April 2021), the Datapool application carries out consistency checks, provides error logs, it is designed to guarantee scalability, and it manages read/write-permission of the different user types. Incremental backups of the underlying SQL database are regularly written; warehouse administration is reduced to a minimum.

While the Datapool (Figure 11.24) development was initially driven by UWO requirements only, over time it was adapted to serve a number of other data collection initiatives. Today, it can be used as a stand-alone tool, the code is made freely available, and it comes with comprehensive documentation (https://datapool.readthedocs.io/en/latest/, accessed 28 April 2021) (credit: ETH Zurich, SIS and Eawag).

11.8.3.2 Data availability and access

All data and meta-data are made publicly available through the web-based platform (TMX http://www.tmx.nl, accessed 28 April 2021) accessible from anywhere. While researchers from external institutions will retrieve the full data as a batch from an open-data repository (in preparation in 2020), the broader public can view collected data series and associated information about monitoring sites in quasi-real-time through this platform.

11.8.3.3 Semi-automated data validation

Due to the shear amount of data currently collected, an automated data validation that goes beyond the standard protocols is required. Firstly, a system-inherent consistency check, i.e. verification of time and data format and a check for real duplicates, is performed when signals arrive at the landing zone, thus avoiding disparate values to be integrated. Secondly, a semi-automatic flagging concept feeds a traffic-light maintenance system allowing for efficient sensor maintenance and quasi real-time data quality control. The principal validation routine includes range, gradient and outlier checks that are individually parameterized depending on signal/sensor type and monitoring site. Thirdly, a data source specific anomaly detection algorithm (Disch & Blumensaat, 2019) allows further identification of doubtful sensor values, indicating sensor failures or abnormal operation situations.

11.8.4 Sensor network operation

11.8.4.1 Maintenance and operational costs

Regular and on-demand maintenance includes sensor cleaning, calibration, troubleshooting, de-/re-installation in case of sewer cleansing, battery change, firmware updates, and LPWAN infrastructure maintenance. Unexpected events requiring on-demand maintenance are condensation of ultrasonic level sensors, corrosion of electrical parts, sensor pollution due to sewer surcharge, poor radio connectivity, and sensor manipulation through third-parties. All efforts add up to 0.25 FTE, i.e. one skilled technician is in duty for more than one day per week. While aiming at minimizing the number of field trips for sensor upkeeping seems a rational idea, it became clear that an excessive reduction compromises a stable sensor network operation and spoils data quality. Day-to-day sensor network maintenance can be considered to make up the highest share of total costs, but clearly guarantees adequate data quality. Hence, planning should focus on strategies to minimize maintenance effort, such as *ex situ* and contact-free measurement techniques, long battery lifetimes, and predictive maintenance through continuous data collection and real-time data validation.

Initial efforts to manage data required an additional 0.25 FTE, in particular during the phase of warehouse development and testing. While sensor network maintenance increases with an increasing number of sensors, costs for data management may level out (0.1 FTE) with a robust and fully established data management framework. Our experience is that initially invested time in conceptual thinking that goes beyond current needs but follows parsimonious thoughts about how to manage data very much pays off in the long-term.

Generally, costs for external services including fees for cellular communication, server storage, LPWAN fees but also rentals (e.g. antenna installation at rooftops) should not be underestimated. They can easily add up with an increasing number of devices. For larger deployments or permanently operated systems in larger utilities, it may be efficient to establish in-house ('private') infrastructure and services.

11.8.4.2 Data communication

Flow sensors and weighting rain gauges transmit their data through conventional cellular modems, accepting all common bottlenecks of this technique: energy-hungry operation requiring battery changes every four weeks, service fees to be paid to the GSM network provider, reception problems for difficult-to-reach locations.

For the LPWAN system, we observed a non-negligible data loss at an early stage of the monitoring programme. Quantifying the radio performance of 25 LoRaWAN sensor nodes – of which 18 were positioned underground – for a 5-month test period revealed the following (Ebi *et al.*, 2019):

- A 12% packet error rate (PER) averaged over the 25 monitored sensor nodes.
- An increasing PER with increasing distance to the central gateway.
- A significantly different PER increase with growing distance depending on the radio node position (above/below ground).
- A threshold of approximately 500 m distance between sensor and gateway for which reception of packets from below ground nodes is good, i.e. with very few packets lost.

Based on a quantitative evaluation in a real-life environment, we concluded that the LoRaWAN technique provides either long-range coverage above ground or medium-range underground connectivity, but not both at the same time. Deployment of additional gateways – one possible solution to overcome range limitations for underground applications – was not an option mainly for three reasons: (i) gateways usually require AC mains power, (ii) costs for gateway installation, management, and internet access increase with the number of installed gateways, and (iii) options to place gateways at adequate locations are *per se* limited (location suitability; legal permission requirements at private properties).

Instead, we developed a new LPWAN concept based on LoRa technology, named synchronous LoRa mesh (i.e. LoRaMesh), a multi-hop data communication (Figure 11.25). With the synchronous LoRa mesh technique we (i) enhance transmission reliability, efficiency, and flexibility in range-critical situations through meshed multi-hop routing, and (ii) ensure a precise time-synchronization through optional GPS or DCF77 long-wave time signalling. Battery consumption at individual nodes is even further reduced since data rates can be higher due to better radio link quality. In two independently conducted long-term field tests under real-world conditions, we analysed the synchronous LoRaMesh sub-network performance with standard LoRaWAN through redundantly installed radio nodes. For the UWO, we compared the performance of 11 synchronous LoRa mesh nodes with 5 standard LoRaWAN reference nodes over an evaluation period of 45 days. We observed a very low packet loss of 2.2%, averaged over all synchronous LoRa mesh systems deployed in this test, whereas some of the standard LoRaWAN nodes did not even connect to the existing gateways. Details including hardware specification, firmware code and test results are provided in Ebi *et al.* (2019).

11.8.4.3 Power management and time synchronicity

Key advantages of the LoRa-based, low-power monitoring are (i) perfect time synchronicity since the network is centrally operated and is synchronized with the internet time, and (ii) extremely low energy

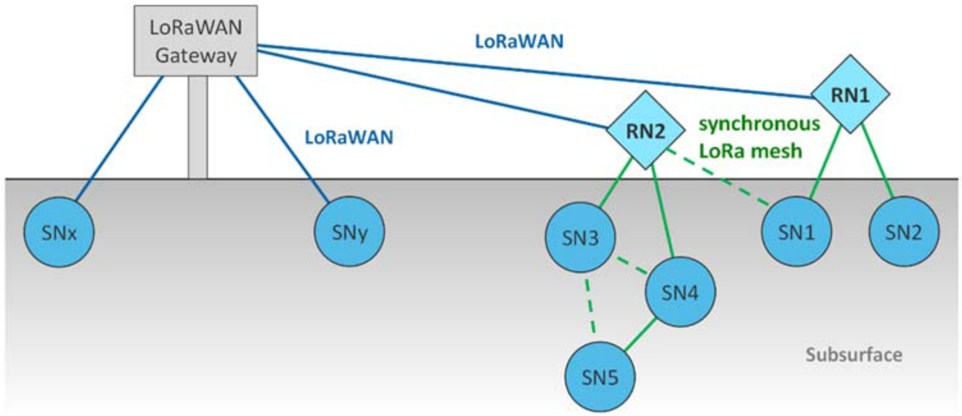

Figure 11.25 Synchronous LoRa mesh topology (RN: repeater node; SN: sensor node). Dashed lines between synchronous LoRa mesh sensor nodes indicate alternative link paths. *Source*: adapted from Ebi *et al*. (2019).

demands, still depending on sensor type, measuring and transmission frequency, data packet size and the signal strength at the given location. More specifically: for a low-power ultrasonic water level sensor measuring and transmitting every 5 minutes, the radio nodes powered by a standard Lithium-Polymer battery – 3.7 V, 6700 mAh – have an estimated lifetime of approximately two years. The same nodes powered by two standard LR20 Alkali-Mangan mono cells – 1.5 V, 18000 mAh – last approximately six years. Practice in the UWO shows that after 3 years of operation (May 2016–May 2019), the very first water level sensor nodes operated at 5-minute intervals still ran on the same set of batteries from installation. Event-triggered adaptive sampling further reduces energy demands, but also decreases the robustness of communication. On the other hand, current research and existing prototypes (https://www.eawag.ch/swp, accessed 28 April 2021) indicate that in the near future we will have energy-autonomous sensor nodes. Initial results show that energy harvesting can be successfully applied to operate underground sensor nodes without any battery.

Given the fact that real-time clocks in sensors and data loggers tend to drift, sometimes considerably, time synchronicity becomes a very relevant issue (see also Section 9.3.5), in the case of large sensor networks and a highly dynamic rainfall-runoff response. For instance, for a few sensors that were operated offline, we observed timestamp deviations of up to 20 min in a period of 6 months. Loggers connected the LoRaWAN inherently provide data with correct time stamps as time syncing with the internet time is ensured through gateways. The maximum latency from the time of the sensor reading to the time the reading is registered at the server is estimated at 6 seconds.

Most of the conventional, off-the-shelf equipment for in-sewer monitoring was certified to meet explosion-proof standards (e.g. ATEX). On the other hand, LPWAN sensor nodes (own prototypes and later externally manufactured) did not have an ATEX certification but were designed and manufactured to be ATEX compliant. A significant advantage of low-power techniques is that the voltages and currents present are inherently so low that, in the event of a fault, the ignition capability cannot be achieved and the equipment can be designed for intrinsic safety according to the ignition protection type. Notwithstanding that certification of commercially available LoRaWAN sensor nodes is under way, it can be debated if equally strict ATEX requirements need to be fulfilled, despite the inherent low-power characteristics of LPWAN devices.

11.8.4.4 Involving the public

Despite there being quite a few sensors positioned above ground and in publicly accessible areas, there are only very few cases (2) of vandalism. Information campaigns, for instance through announcements and articles in local newspapers, give-away flyers, a well-developed project website, informative display panels installed next to sensors/antennas and – at a later stage – public information events very much help to make residents aware of ongoing monitoring and create a 'participative moment'. Returning useful information in the form of a living dashboard at which prepared data are visualized, at best in real-time, also helps to attract positive attention in the local public. We are convinced that Public Relations work is well-invested time as it has helped to establish the project and to ensure a smooth operation of the UWO.

11.8.5 Hardware cost considerations

The net present value of the currently installed sensors and wireless communication infrastructure adds up to an estimated CHF 120,000 (€ 106,000) for conventional sensors (rain, flow) and CHF 60,000 (€ 53,000) for the LPWSN including LPWAN infrastructure. An additional CHF 20,000 (€ 17,500) are accounted for groundwater multi-parameter monitors, and a further CHF 5,000 (€ 4,400) for installation material is required. Investments for the LPWSN are comparably low, in total and specific for the sensor node. Based on a conservative estimation for an in-house prototype node with a standard low-power water level sensor built in 2017 we estimated specific costs of CHF 125 (€ 110) per year. In other words, a water level pattern for one day assuming a 5-minute measurement interval costs € 0.30. This estimate includes (i) the costs for hardware components for the LoRaWAN sensor node (Eawag prototype), the water level sensor (Maxbotix), batteries (standard D cells), 5% proportionate costs for the LoRaWAN gateway device (assuming a depreciation over five years for all), and (ii) the costs for external services, such as LPWAN backend management and data dashboard services. While the costs for hardware components are expected to decrease significantly in the future, service fees may remain in the same order of magnitude. Overall, the total costs for LPWAN based measurements is expected to further decrease.

11.8.6 Main findings and lessons learnt

The main findings from the UWO monitoring project can be summarized as follows:

(1) Low-power sensor technology combined with a very efficient LPWAN technique (Ebi *et al.*, 2019) considerably facilitates data collection in underground infrastructure. Low energy demands, nearly unlimited scalability, time synchronicity and very low specific costs increase the efficiency when collecting data, and enables harvesting more reliable information through signal redundancy and diversity. Generating truly spatially distributed information in quasi real-time becomes a reality. Still, the availability of such new data sources opens up new challenges regarding data management, and institutional and regulatory requirements that need to be adapted likewise. In the preparation of a sensor node deployment, exploratory analyses of available link budgets on site are essential to avoid upsets regarding high packet error rates due to poor radio connection.

(2) Dynamic and flexible data management solutions come at a price. It is not the pure amount of data that is most challenging, but the diversity of different signals. Within this context, full meta-data integration in the data management process is laborious but clearly consolidates data interpretation in the long-term. Changing data formats and server settings, and the lack of

standardized protocols hamper efficient data management. Standards and protocols that link operational and infrastructure data need to be established/harmonized based on research and practical experience.

(3) The use of simple and robust capacitive sensors for overflow activity monitoring is an efficient method to reliably estimate urban drainage emissions. Such information can also be utilized to calibrate hydrodynamic models (Wani *et al.*, 2017). Information content increases when censored signals, i.e. signals that are constrained e.g. to provide 0/1 information, are combined with uncensored information from parallel installed water level sensors.

(4) The performance of (emerging) data validation techniques, and hence future use of the data, is dependent on the quality of the collected data and the corresponding pre-processing. No matter which data validation technique is applied, careful sensor set-up and configuration is priceless in order to obtain a meaningful dataset (Disch & Blumensaat, 2019).

(5) Direct access to sites, short travel times between headquarters and the study catchments, real-time data communication and automated validation is key to keep the maintenance effort low. Early and transparent information to the public, and sound and trustful collaboration with the local operator and municipality is key to success.

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