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Implementation of a Real-Time decision support system to reduce pollutant load- discharges in Madrid combined sewer system based on off-line and real time modelling

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Abstract
The LIFE RUBIES project aims to develop and deploy an operational tool in Lille (France) and Madrid (Spain) to reduce the impact of combined sewer overflows (CSO) during rain events, by controlling water pollution in real-time. Real-time control will enable decision making over the flow and storage of urban wastewater to prevent pollution, leveraging the coupling of sensors, models, and controllers. This paper presents the work conducted in the Madrid case study to implement and test the system, improving the operation of part of its sanitation facilities (two stormwater tanks with a total capacity of 600.000 m^3, two wastewater treatment plants, and the corresponding sewage network), and showcases some preliminary results.
The project started in October 2021 and will conclude in December 2025.

Highlights
- Characterisation of pollutant loads in dry and rain events for combined sewer systems
- Combined Sewer Overflow (CSO) mitigation.
- Real-time control operation of drainage and sanitation systems.

Introduction
The Madrid metropolitan area faces significant challenges in managing its urban drainage system. The sewage network, mostly combined, has approximately 16,000 km of sewers, and about 90% of the catchment area discharges into two main interceptors that run parallel to the Manzanares River. Despite the existence of several stormwater tanks and wastewater treatment plants, the system's capacity is often exceeded, resulting in polluted waters being discharged into the river through combined sewer overflows (CSOs). It is to be highlighted that Manzanares River has practically no natural flow, so river quality is very much sensitive to CSO discharges.
In response to these challenges, Canal de Isabel II has undertaken a process of digitalization of its sanitation and drainage infrastructure, with the European LIFE RUBIES project being an important part of this process. The project aims to develop and deploy a decision support system with a Model

Predictive Control (MPC) module for optimizing the sewage system operation through real-time quality based predictive control (this means that it focuses in reducing the pollution load discharged to the river, not only the CSO volume). The goal is to improve the ecological status of the Manzanares River and demonstrate the effectiveness of this approach in addressing environmental problems caused by urban water networks.

Methodology

The LIFE RUBIES project focuses on reducing water pollution in the Manzanares River basin by implementing a quality based, real-time control system for managing the sewer network. The following sections describe the different components of the methodology used in the project.

Sewer Network Monitoring

To monitor the sewer network, turbidity and conductivity sensors have been installed to complement other existing sensors with the goal of obtaining a continuous measure of wastewater flow and pollutant concentrations. These sensors are located near sewer discharge points to calculate pollutant emissions. The monitoring station schemes have different configurations depending on the sewer location, cross section and the site maintenance difficulties, e.g. sensors piped in the collector wall, floating with the flow or offline measurement with the aid of a peristaltic pump which sends water from sewer to a sedimentation tank where the probes are located).

Water Quality Characterization

In addition to continuous monitoring, automatic samplers are being installed to conduct water quality characterization campaigns under dry and wet weather conditions. More than 200 analyses were performed in 3 location points, with at least 2 dry weather campaigns and 3 rain events campaigns at each point. A total of 12 water samples were taken in each of these campaigns, with resolution varying between 1 hour in dry weather and up to 20 min in rain episodes. Combining the quality results obtained with overflow estimation obtained from level meters located in the discharge points, the corresponding hydrographs and pollutographs are obtained, enabling comparison of water quality parameters between dry weather and rainfall events.
With the information provided by these field campaigns and the continuous monitoring quality parameters (turbidity and conductivity) it was possible to:

- Obtain correlations between turbidity and non-soluble contaminants (suspended solids, DQO and DBO5) and conductivity and soluble contamination (Ammonia, Total Phosphorus and Total Nitrogen) for dry weather flow and for rain events. Based on these correlations, from the continuous measurement of turbidity and conductivity, a real time estimation of the discharged CSO pollution can be obtained.
- Compute Mean Event Concentrations (MEC) for the previous pollution parameters to transform CSO’s volumes to mass pollution discharged to the river. The results obtained were completed with the ones from a previous study (Lastra et al. 2018) to obtain the MEC for each of the CSO discharging points in the pilot area.

The results of monitoring campaigns show that the pollution discharged by CSOs (Combined Sewer Overflows) during rainfall events is significant, with peak values sometimes even higher than those recorded during dry weather, confirming the findings of previous studies conducted in Madrid (Lastra et al. 2018).

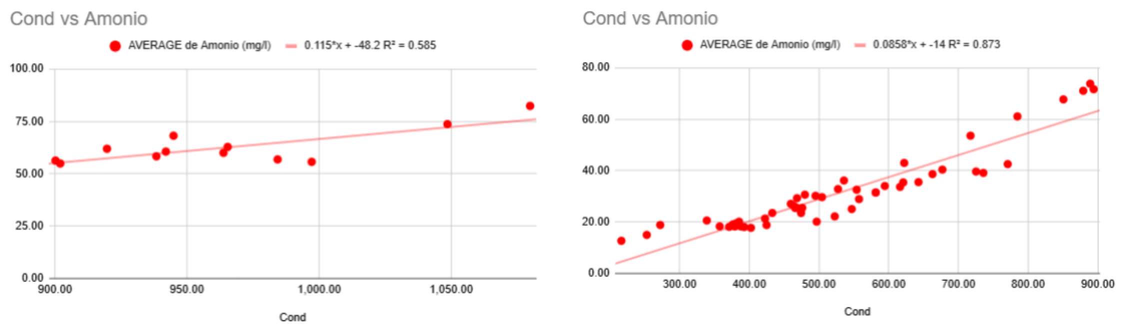

Figure 1. Conductivity vs Ammonia correlations in Sur WWTP influent. Left DWF correlation, right rain events correlation.

Table 1. Mean Event Concentration for the different CSO locations from the pilot site obtained from the water quality campaigns accomplished during rain events.

CSO location	SS (mg/l)	COD (mg/l)	Ammonia (mg/l)	Ptotal (mg/l)	Ntotal (mg/l)	BOD5 (mg/l)
EDAR Sur	410.61	705.8	26.06	6.09	36.23	335.83
Entrada EDAR But	297.27	395.97	11.4	2.88	16.73	201.15
Primari EDAR But	120.48	332.31	40.55	5.17	37.94	170.89
Partidor But	325.54	616.37	18.31	5.3	23.27	329.57
Aliv Sur	135.08	308.19	13.28	3.06	17.15	163.58
Abroñigales	139.39	380.99	8.58	2.62	11.75	201.19
Average	238.06	456.61	19.7	4.19	23.85	233.7

Rainfall Prediction

Rainfall prediction is a crucial input variable for the model simulator. Initially the project implemented radar data from AEMET (Spanish National Meteorological Agency) but validation against ground-based rain gauges for 6 rain events revealed a daily rain average error of 90%. Under this circumstance, Canal de Isabel II´s radar monitoring system was used, which proved to have a smaller error (24%). This system is based on three X-Band radars, which provide a unique composition file with current rainfall measurements and a 2-hour rain forecast. These files are updated in the Decision-Making model every 15 minutes.

Sewer Network Modelling

A detailed model of the sewer network and associated infrastructure has been developed using SWMM software. The hydraulic model has been calibrated with 24 rainfall events (from March 2024 until March 2025) with the water level and flow sensors available. The average CSO volume error is of 34%, with a maximum error of 271% for the rain event of 8/6/2024 and a smallest one of 1% for the 1/3/2025.

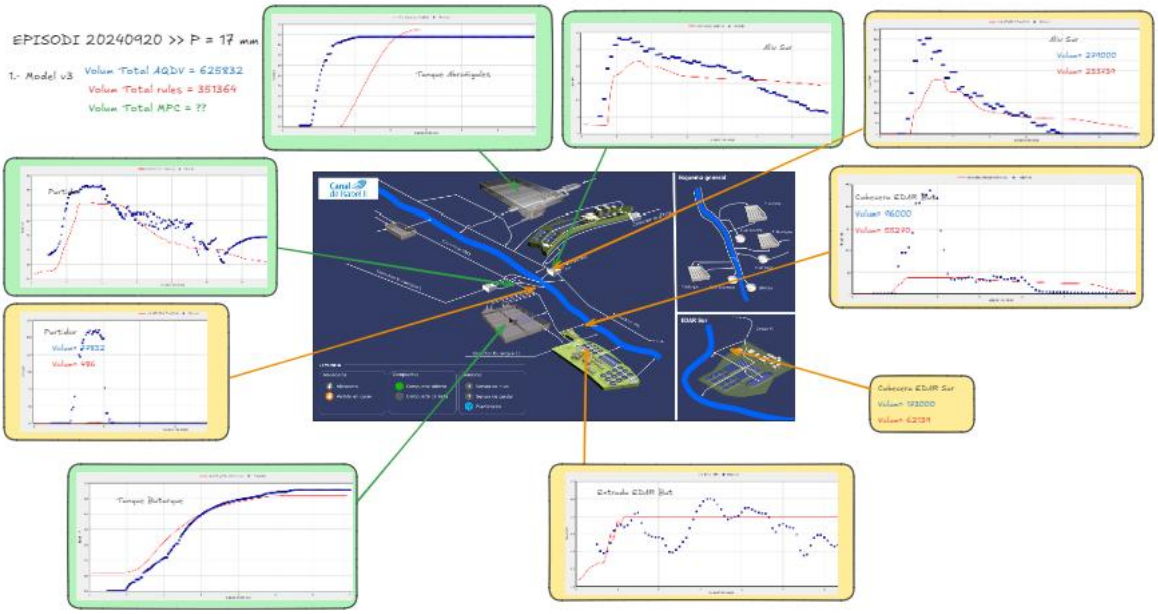

Figure 2. Example of calibration results graphs (flows and water levels for the rain event of 20/9/2024. For this rain event an error of 36% in CSO discharge volumes is obtained.

This model is configured to run online with inputs from the real water level sensors in the tanks and real and forecasted rain data to provide the expected sewer system evolution for the coming two hours (tank volumes, sewer levels, and CSO flows mainly). This expected model response is used as useful information to provide better setpoints recommendations for the actuators.
After several months operating the system with the SWMM model configured it is evidenced that model results differ significantly from the real data measurements. Three main reasons can justify this circumstance:

- The offline model as described previously has some lack of basic information (sewer slopes, sewer cross sections and manholes heights and connections that were inferred from surrounding data)
- The rain data used coming from radar is underestimating the real rain by an average of 23% (varying from 5 to 62% depending of the specific rain event)
- The pilot area is located in the final stretch of the Manzanares sewer system. Upstream there are other tanks and actuators that in the model are implemented based on generic operational rules but the real operation of this infrastructure for different rain events may vary significantly.

Decision-Making Model

A Model Predictive Control (MPC) solution developed and tested offline in Life Effidrain project (Sun, 2021), is integrated into the AQUADVANCED URBAN DRAINAGE software.
The strategy module will use all contextual data provided by the sensors installed in the network, rainfall data, and short-term weather forecasts, as well as the online SWMM model forecasted values to provide a management strategy adapted to the current and future operational context. An optimization rule will be implemented in a control-oriented quality model procedure, using algorithms based on the linearization of the hydraulic and quality equations of the network. The objective function will consist of a mathematical representation of the operational goals to be defined, such as avoiding flooding and minimizing sewer discharges pollutant load.

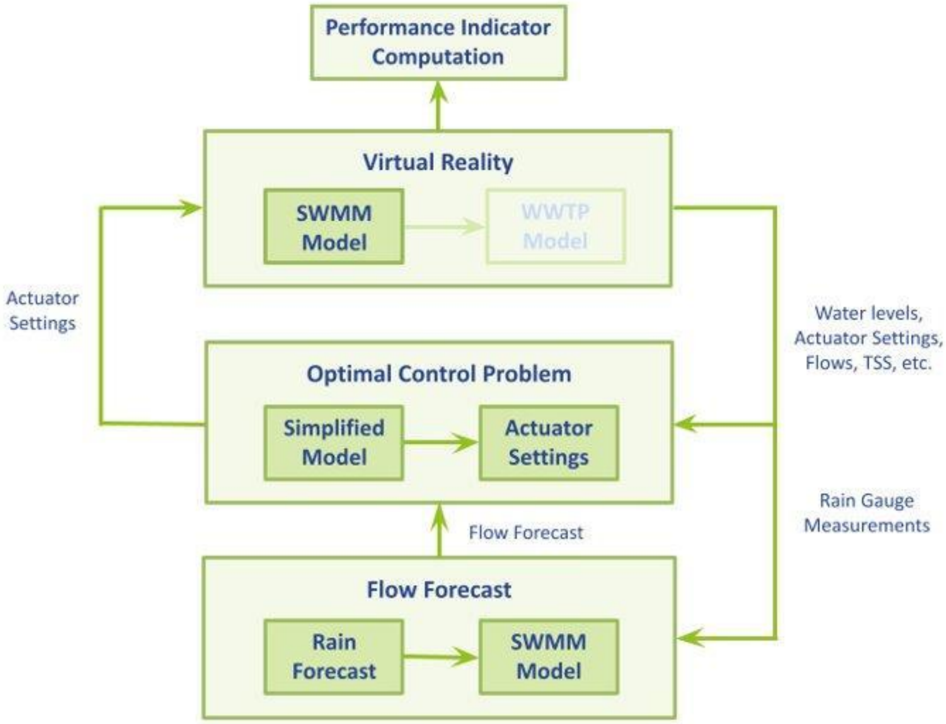

Figure 3. Real time closed-loop between real sensor values, SWMM model forecasted results and MPC model to obtain actuator setpoints to be implemented.

Real-Time Control Application

The real-time control application is based on the AQUADVANCED URBAN DRAINAGE software (AQDV), which provides real-time monitoring and control of the sewer network sensors and actuators in connection with the Canal de Isabel II Central SCADA. This tool enables the view of real-time data collected by meteorological services and measuring equipment deployed in the network, launches the SWMM model and the MPC, and provides recommended setpoints for the system actuators (pumps and gates positions) so that operators can manually validate and apply them through Canal de Isabel II SCADA.

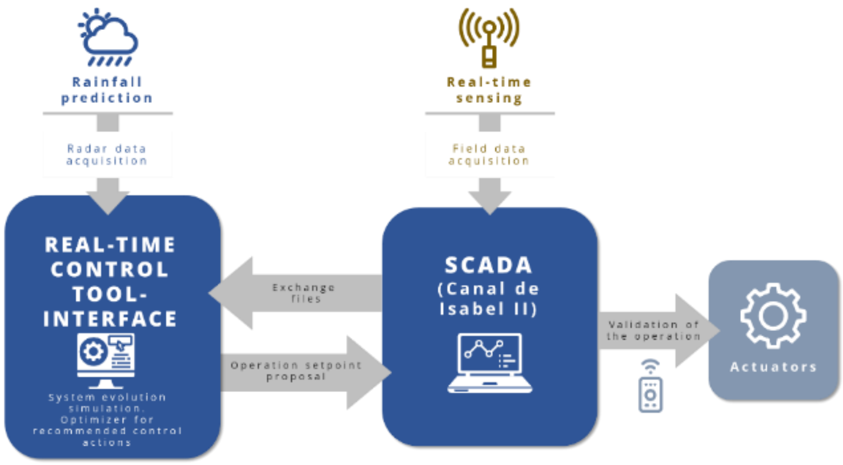

Figure 4. Real time control scheme implemented in AQDV

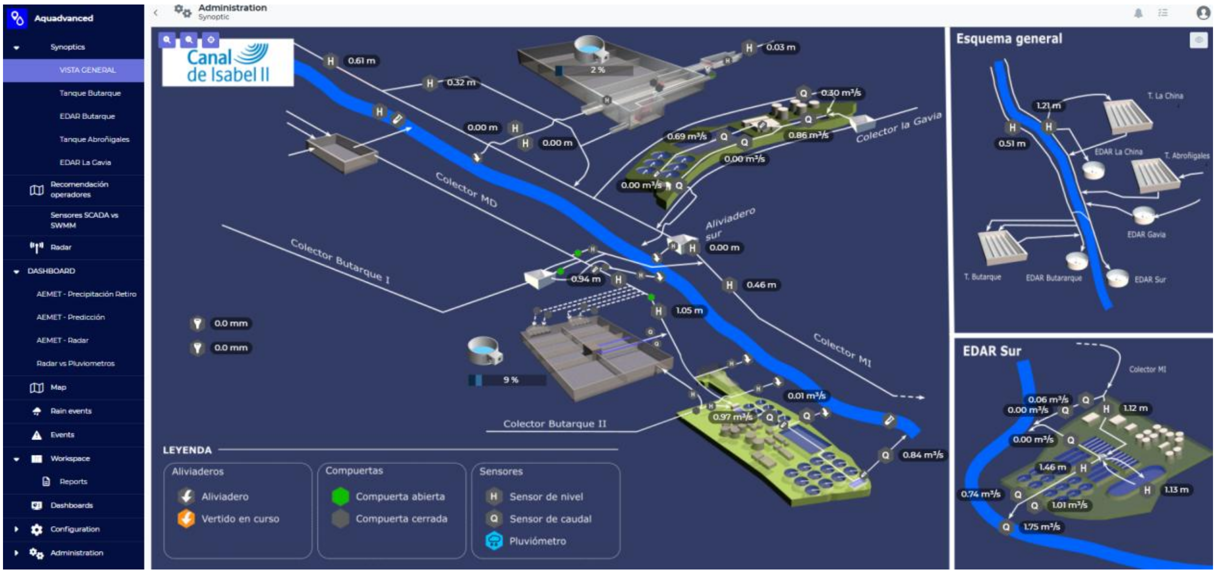

Figure 5. AQDV pilot area synoptic view

River Water Quality Monitoring and modelling

To monitor river water quality, control monitoring points have been defined upstream and downstream of the Manzanares River stretch within the pilot area. Continuous monitoring of classical parameters (organic matter, DO, temperature, EC, ammonium, nitrates, pH, turbidity/SS) will be used to calibrate a computer river model. This numerical river quality model is being developed using the IBER river modelling tool. It will be used to evaluate the impacts of sewer discharges and the expected benefits of a quality-oriented management of the sewer system. This task is ongoing at the time being.

Results and discussion

Since October 2023, AQDV has been running 24/7, gathering real-time data from rain gauges, radar, flow levels, water quality sensors, and actuators at the pilot site. AQDV operation strategy has been evaluated during the period from March 2024 to July 2025. Throughout this timeframe, over 25 rain events were analyzed in real-time to validate AQDV's recommended setpoints and assess their operational effectiveness. This analysis included monitoring operator-implemented setpoints to identify potential improvements in operational protocols, which were subsequently discussed through post-event communications and meetings.

A significant outcome of the LIFE RUBIES project has been the substantial enhancement of Canal de Isabel II operational strategy, particularly evident during the analyzed 18-month period. This evolution is demonstrated by the marked difference in handling similar rain events between 2024 and 2025, reflecting tangible improvements in reducing CSO discharges and their impact on the water quality of the receiving water body.

The assessment of operational improvements presented unique challenges in terms of direct before-and-after comparisons. Two main factors complicated this evaluation: first, the inherent difficulty in finding identical rain events for comparison between pre-and post-LIFE Rubies periods; and second, the gradual implementation of operational improvements, which began in 2023 and continued through September 2025, with further enhancements planned in the After-LIFE phase.

To address these challenges, KPIs were calculated using model-based simulations of real rain events that occurred between March 2024 and September 2025. Two scenarios were developed:

- **The baseline scenario:** The before-LIFE scenario utilized the SWMM sewer model implementing the previously established operational protocol rules adopted by Canal de Isabel II.
- **The enhanced scenario**: The after-LIFE scenario used the same model but incorporated MPC-computed setpoints for the pilot area's main actuators (pumps and gates), replacing the original standard operational protocols used by Canal de Isabel II.

Improvements in Canal operation strategy

Since the project's inception in late 2021, several improvement strategies were identified in the management of the Manzanares system, particularly concerning the pilot zone actuators. A significant enhancement opportunity lays in the possibility of carrying out an integrated management. The absence of a centralized decision-making system leads to each operator deciding on their own structure (whether a Stormwater tank or a WWTP) without having a context that allows them to collaborate in searching for a global coordination.

In this sense, the LIFE-RUBIES project and AQDV implementation have successfully facilitated information sharing among operators, providing a comprehensive system-wide operational view.

A second major improvement area addressed communication of operational actions. While tank filling operations were already automated through established protocols and PID-controlled setpoints, tank emptying remained a manual process requiring telephone coordination between each of the tank´s operators and WWTP staff during working hours to determine operational status, emptying priorities, and deciding setpoints which were communicated again by phone.

Besides these general procedures, three major improvements in specific operation strategies have been achieved in these months:

- **Reduction of CSO discharges in right margin interceptor by improving Butarque tank filling operations:** Early analysis of rainfall events revealed significant improvement opportunities in Butarque tank filling operations as it was evidenced that CSOs was taking place before the tank reached its maximum storage volume. Progressive improvements were implemented mainly related with anticipating and accelerating the tank filling by means of closing the bypass gates located downstream the tank entrance until the tank is 100% full.
- **Reduction of CSO discharges in left margin interceptor by improving Abroñigales tank filling:** The original intention was to implement the same strategy as in the right margin interceptor and completely close the Abroñigales tank bypass gate to accelerate the filling operation. However, there was a risk of gate malfunction if closing exceeded an established threshold. For this reason, an alternative procedure was implemented to increase tank filling velocity and prevent CSO. This consisted on lowering the crest of the lateral weir of the tank inlet. This intervention quickens tank filling operation and significantly reduces the chances of CSO occurring downstream.
- **Improving Tank emptying:** deviations observed in the real system management highlight the limitations consequence of not having a programmed operation scheme. This circumstance leads to unfortunate situations such as extended periods of tank emptying which impact on stored water quality and reduce storage availability for future rain events. At the project's start, tank emptying management was highly conservative due both for technical decisions but also for technical constraints (lack of remote control capabilities, manual operation was limited to working hours, etc.). As the project progressed emphasis was placed on accelerating emptying processes, particularly during night hours when WWTP inflow is reduced.

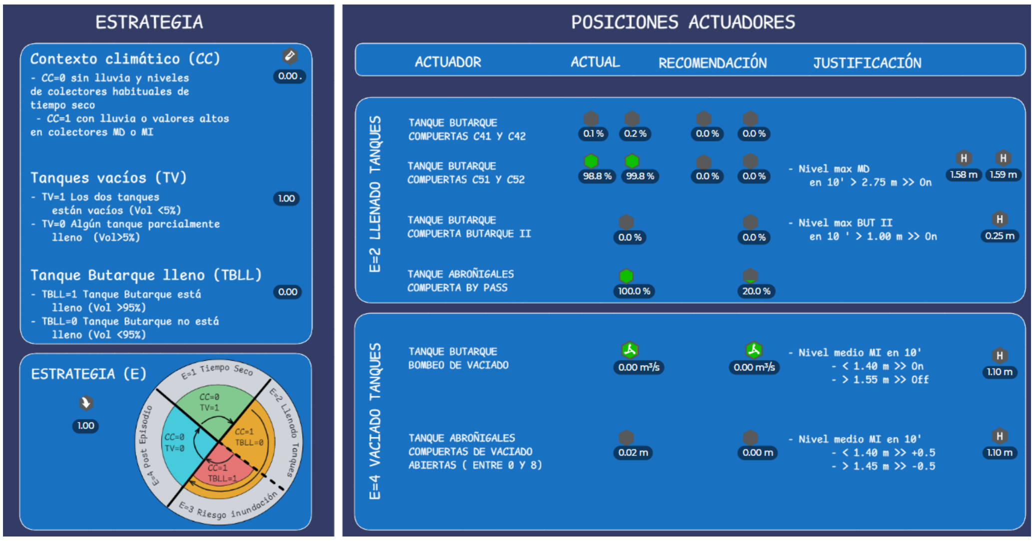

Figure 6. AQDV recommendation setpoints screen informing the current strategy and the recommendation for the operators.

CSO volume reduction KPIs

As described previously a comparison based on modelling results has been made comparing 24 rain events (although some events included several rain events between short dry periods, but still to close on to the other as to enable tank emptying).

The results for each rain event are presented in Table 2, and the following key ideas can be highlighted:

- The average benefit from MPC scenario vs baseline scenario is close to a 28.5 % reduction of the total CSO volume discharged to the Manzanares river.
- The smaller the rain event is, the bigger benefit can be obtained. On the opposite, for big rain events the benefit is smaller. This is reasonable considering there is a maximum water volume that can be managed. If the rain event volume clearly exceeds the total storage capacity no matter which is the operation procedure, the percentage benefit obtained is smaller.
- MPC scenario can even reduce floodings in case of big rain events.

Similar or a bit higher percentage improvements are achieved considering different pollution parameters such as SS, BOD, Ammonia, etc.

Table 2. KPIs CSO volume and flood volume reduction improvement between the baseline scenario (SWMM rules results) and the enhanced scenario (MPC results)

Rain Event				SWMM rules results		MPC results		Analysis		
				CSO	Flood	CSO	Flood	Improvement		
Date	Rain (mm)	Duration (h)	Rain Average (mm/h)	Total (m3)	Total (m3)	Total (m3)	Total (m3)	CSO	Flood	Total
08/03/2024	11.4	7	1.63	256506	14135	159819	505	37.69%	96.43%	40.76%
11/03/2024	11.8	8	1.48	286955	13996	180638	498	37.05%	96.44%	39.81%
28/03/2024	11.8	6	1.97	216700	9287	122851	9247	43.31%	0.44%	41.55%
27/04/2024	7.8	14	0.56	81680	0	45775	0	43.96%		43.96%
08/06/2024	4.2	5	0.84	42706	0	21169	0	50.43%		50.43%
10/06/2024	29.8	8	3.73	721329	244692	769052	166609	-6.62%	31.91%	3.14%
20/09/2024	17	3	5.67	369011	78924	242942	51199	34.16%	35.13%	34.33%
07/10/2024	5.2	3	1.73	74080	0	36509	0	50.72%		50.72%
12/10/2024	21.9	11	1.99	463435	150680	354960	114068	23.41%	24.30%	23.63%
16/10/2024	13.2	28	0.47	301213	12370	211395	2878	29.82%	76.73%	31.67%
29/10/2024	23.6	16	1.48	608641	154863	570723	104103	6.23%	32.78%	11.61%
01/11/2024	9.6	1.5	6.40	223963	12864	189612	13213	15.34%	-2.71%	14.36%
20/01/2025 - 3 days rain	21.4	76	0.28	566020	11896	388092	2064	31.43%	82.65%	32.49%
27/01/2025	5.6	5	1.12	63865	0	32503	0	49.11%		49.11%
29/01/2025	5.4	8	0.68	42985	0	18072	0	57.96%		57.96%
11/02/2025	14.2	7	2.03	415243	57742	276220	19512	33.48%	66.21%	37.48%
01/03/2025	18.2	40	0.46	560330	79500	367780	34545	34.36%	56.55%	37.12%
03/03/2025 - 7 days	64.8	168	0.39	2955366	442662	2591944	264896	12.30%	40.16%	15.93%
10/03/2025 - 7 days	45.4	168	0.27	2221076	299597	2133871	200305	3.93%	33.14%	7.40%
17/03/2025 - 7 days	51.4	168	0.31	2386118	262732	2068562	184128	13.31%	29.92%	14.96%
03/04/2025 - 2 days	47.4	48	0.99	2269013	425818	2342583	260496	-3.24%	38.82%	3.40%
11/04/2025 - 3 days	24.4	98	0.25	1027721	69940	704315	28024	31.47%	59.93%	33.28%
18/04/2025 - 2 days	12	13	0.92	374494	12184	300350	6368	19.80%	47.73%	20.68%
02/05/2025 - 1 days	29	24	1.21	1060511	211461	1117678	123533	-5.39%	41.58%	2.42%

Conclusions and future work

The LIFE RUBIES project has highlighted the importance and benefits of using digital based solutions for the operation of complex urban drainage systems. This deployment relies on very short anticipation weather forecasting, and drainage infrastructures modelling and sensorization.

Results obtained from the Pilot Site Case Study are encouraging and evidence that CSO discharges which can occur during rain episodes, both in terms of their magnitude and the concentration of their polluting load, can vary greatly depending on the operation of the urban drainage infrastructure. The Decision Aid Tool presented in the Life Rubies project enables a centralized operation of the whole sanitary system and serves as support for making decisions in real time operation.

Based on this experience, Canal de Isabel II, is now accomplishing an ambitious plan of digitalization of the whole of the Manzanares Sanitary System, thus extending upstream the pilot site case study area. This action will be accomplished within an NextGeneration EU funding program.

Focusing on the Life Rubies case study, the project is set to conclude in December 2025, with this year's work focused on better integrating the SWMM model and MPC module into AQDV to enhance real-time management during rainfall events. Other key activities include completing characterization campaigns in river, as well as assessing the impact of discharges on the Manzanares River through river modelling. This will enable the application of water quality results to inform actuator management and drive continuous system improvement through the reanalysis of rainfall events from 2024 and future ones in 2025. Achievement of this goal will be accomplished by means of implementing control instructions calculated by AQDV and conducting post-rain event analysis with operators.

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