Dynamic Simulation of Wastewater Drainage Systems Performance

The Case of Águas de Santo André S.A System, in Sines, Portugal

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Abstract: In recent decades, the concern about water resources and the high complexity of urban drainage systems have fostered the use of mathematical models, which have been shown to be a useful decision-making tool for planning, design, and management of wastewater infrastructures. This dissertation proposes to analyse the dynamic performance of an urban wastewater drainage system by applying the Storm Water Management Model (SWMM) simulation model developed by the United States Environmental Protection Agency (USA-EPA) to a real case study, Santo André wastewater drainage system with significant industrial contributions. The hydraulic model was calibrated and validated with field data collected by climate and hydraulic variables monitoring networks available in the study area using a pseudo runoff coefficient (C'), reflecting the pseudo separative character of the system.

The hydraulic performance of the system was analysed according to two simulation types of scenarios. The first scenario is intended to estimate the amount of storage needed under dry weather, in case the WWTP operation is interrupted for 2h, 4h, and 6h. The second scenario aims to optimize the capacity of the WWTP at the expense of increasing the storage or volume for rainfall events with a frequency of 1x/year, 5x/year and 10x/year. In case of interruption of the WWTP, an additional storage becomes necessary, depending on downtime periods, beyond the two existing ones.

For the occurrence of significant rainfall events, the proposed additional storage to avoid overflows is estimated in about 700 m^3.

Keywords: wastewater, urban drainage, mathematical modelling, petroleum and petrochemical industries wastewater; monitoring of climatic and hydraulic variables, SWMM.

Introduction

With the increase of built-up areas and impermeable zones of urban areas, the occurrence of discharges of contaminated overflows to the receiving water has increased. In general, these discharges contain high pollutant loads, responsible for the degradation of water quality, which compromises the fulfilment of the quality objectives (David et al., 1998).

Improper discharges can occur as a result of excessive flow, due to the occurrence of severe rainfalls or by temporary limitation of the transport capacity of the drainage system. Because these events are not always predictable, there may be little available time to act (Brito, 2012). Hence, the effective and efficient management of the drainage system should be based on an appropriate monitoring network that allows the utility in charge to make a decision and intervene in a timely manner to minimize its consequences (Ferreira, 2006). In this context, and in the need to develop increasingly complex urban drainage infrastructures, computer modelling has shown particular utility in the effective management of wastewater drainage systems.

The aim of this study is to analyse the hydraulic performance of the Santo André wastewater drainage system, which is in charge of Águas de Santo André, SA, of the Águas de Portugal Group (AdP), through the development and calibration of a dynamic simulation model based on the Storm Water Management Model (SWMM). Additionally, a monitoring strategy is presented with an emphasis on precipitation measurement and hydraulic variables, namely flow depths, velocities and flow rates.

The relevance of the analysis of the Santo André wastewater drainage system is associated with the fact that this system receives industrial effluents characterized by its toxic composition, rich in hydrocarbons and sulphides that, in a situation of overflows, can cause particularly harmful effects on the receiving water bodies.

Case study

The management and operation of the Santo André System is under the responsibility of Águas de Santo André, SA (AdSA), a company of Grupo Águas de Portugal that supplies water to the population, collects and treats wastewater and meets the needs of industries located at ZILS in terms of potable and industrial water, wastewater and industrial waste (Águas de Portugal, 2019; Decreto-Lei nº171/2001).

Its activity is developed according to the following geographical limits, Municipalities of Santiago do Cacém and Sines including Sines Industrial and Logistics Zone (ZILS). Being responsible for the collection, transport, treatment and final disposal of urban wastewater from the cities of Vila Nova de Santo André, Santiago do Cacém and part of the wastewater from the city of Sines, and from industrial and saline wastewater from ZILS.

The Santo André wastewater drainage system currently collects, transports and treats industrial wastewater from the following companies located at ZILS: Petrogal - Galp Energia Sines Refinery, Repsol Polymers, Euroresinas, Indorama (formerly Artlant), Enerfuel, Air Liquide and Ibera (**Table 1** and **Figure 1**).

Table 1 – Client companies producing industrial effluents.

Company	Activity
Galp Energia	Refinery
Repsol Polímeros	Petrochemical
Euroresinas	Formaldehyde and Synthetic Resins
Indorama (formerly Artlant)	Purified terephthalic acid production (PTA)
Enerfuel	Biofuels
Air Liquide	Gas production
Ibera	Concrete industry

The Santo André wastewater system lies over an area of approximately 104 km^2 and consists of several outfalls and has a total length of about 62 km. It has eleven wastewater pumping stations, one oxygen injection station, two retention basins with capacities of 5 000 m^3 and 7 000 m^3, one WWTP with a capacity of 500 L/s and a 2.4 km sea outfall (Águas de Santo André, 2019).

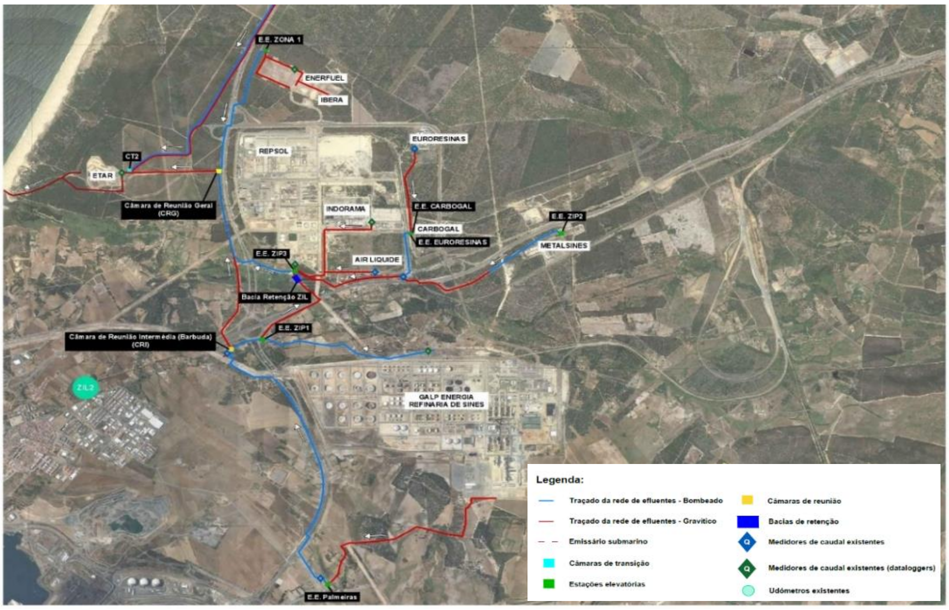


Figure 1 – Santo André drainage network general plan (Águas de Santo André, 2014).

Wastewater outflowing to the system is predominantly industrial. About 75% of the wastewater that flows into the Santo André wastewater system is industrial and approximately 25% is domestic. In 2018, the WWTP treated 5 415 598 m^3 of industrial wastewater and 1 578 037 m^3 of domestic wastewater.

In the area under study, three meteorological stations are available for monitoring, two in Sines, located near the ZILS industrial complex, APS and ZIL2, and another located in the RESIM landfill.

There are currently 12 flow measurement points in the drainage network under study, of which 5 are relevant for monitoring as they are equipped with data acquisition systems (dataloggers) (**Figure 1**).

Methodology

Developed by the USA Environmental Protection Agency (EPA), the Storm Water Management Model (SWMM) software is a dynamic 1D model for simulating the flow and transport of pollutants to the surface of drainage basins and within conduits, (Rossman, 2015). For the purpose of hydraulic modelling, SWMM version 5.1.013 was used in this study.

According to Olsson and Newell (1999) and Dochain and Vanrolleghem (2001) quoted by Ferreira (2006), the modelling process involves the following steps:

1. Problem definition and model objectives;
2. Collection of information (registration);
3. Selection of the model to be applied, considering the purposes for which the model is intended;
4. Establishment of initial and boundary conditions;
5. Discrete representation of differential equations by numerical methods;
6. Code development and debugging;
7. Model calibration and validation;
8. Application of the model.

a) **b)**

Figure 2 – Conceptual representation of the hydraulic (a) and hydrological (b) model of the Santo André wastewater drainage network - SWMM.

In order to achieve the objectives of this study, the first step was to collect the registered information of the Santo André wastewater system and collect the necessary data for its operation with AdSA. Once the hydraulic and hydrological model was built (**Figure 2** (a) and (b)) it was calibrated and validated for dry and wet weather.

For the definition of the inflows to the system under dry weather, daily flow measurement data obtained through electromagnetic flowmeters installed in the following locations were used: E.E. de Santo André, at E.E. ZIP3, in E.E. RESIM, in E.E. Palmeiras, at the Intermediate Meeting Chamber (CRI) and outside the client industries Euroresinas, Repsol, Enerfuel, Petrogal, Indorama and Air Liquide.

In the calibration and validation of the dry weather model, we used the instantaneous flow records measured at the entrance of the Ribeira de Moinhos WWTP through an ultrasonic flowmeter and at the exit of the Indorama, Repsol and Enerfuel industries, collected by electromagnetic flowmeters.

Historical rainfall records used for calibration and validation of the model in wet weather were collected by ZIL2 precipitation gauge. Given the scarcity of information in terms of flow measurements for the year 2019, the calibration and validation process of the wet weather period model was performed with 2017 rainfall events and flow measurements.

For the calibration of the model in wet weather, a methodology was adopted to establish the relationship between precipitation and the volume of rainfall contribution to the WWTP. A coefficient representative of the relationship between precipitation and runoff (C') was determined from expressions 1 and 2, which was assigned the designation of the “pseudo runoff coefficient” that, after calculation, was entered into SWMM for model validation.

$$V_{rain\ contribution} = V_{measured} - V_{medium\ TS} \quad (1)$$

$$C' = \frac{V_{rain\ contribution}}{P_{event} \times A_{total}} \quad (2)$$

Where:

$V_{rain\ contribution}$ – is the volume of rainfall contribution at the entrance of the WWTP (m^3);

$V_{measured}$ – is the daily measured volume at the entrance of the WWTP (m^3);

$V_{medium\ TS}$ – is the average volume of dry weather at entrance of the WWTP (m^3);

C' – is the pseudo flow coefficient (-);

P_{event} – is the precipitation of the event considered (mm);

A_{total} – is the area of the sub-watersheds that contribute to the WWTP.

In both dry and wet periods, the calibration process was performed considering 2/3 of the available data and the validation process considering 1/3.

After the model calibration and validation process, different scenarios were simulated.

Simulation scenarios

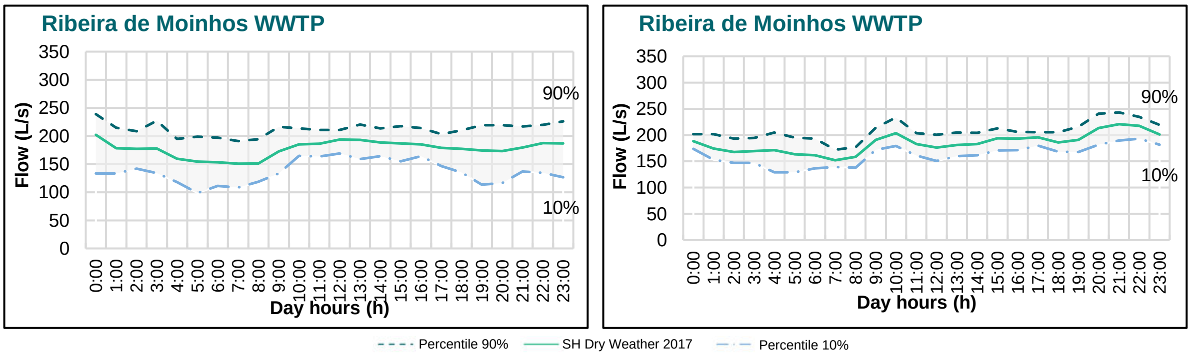
Dynamic simulation was used to achieve a more detailed knowledge of the system's operation in the presence of different requests and the optimization of its performance, taking advantage of existing infrastructures. Thus, two distinct types of scenarios were formulated:

- **Scenario type A** – It was intended to estimate the necessary storage volume under dry weather, in case of interruption of the Ribeira de Moinhos WWTP operation during 2h, 4h and 6h;

- **Scenario type B** – It was intended to improve the performance of the system by increasing the storage or regularization volume, without discharging any precipitation events with an annual frequency of 1x/year, 5x/year and 10x/year, assuming the presence of a storage near the WWTP (end-of-line storage).

For the constitution of the series of days of dry weather, the criterion used was considering the days of zero precipitation or with daily accumulated precipitation equal to or less than 0.5 mm and precipitation intensity <0.25 mm/h. A daily sampling period of 15 days was considered for which flow measurement data were available, 11 weekdays and 4 weekend days, between June 28 and July 12, 2019.

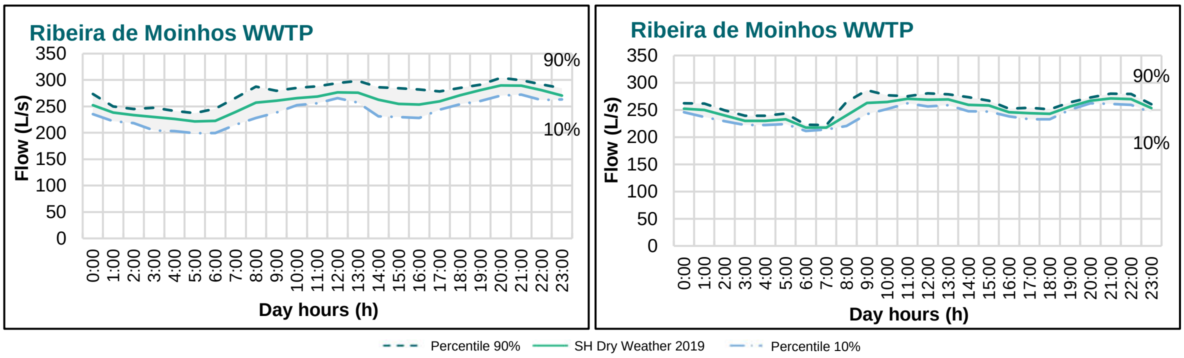
From the dry weather instantaneous flow records at the entrance of the Ribeira de Moinhos WWTP, it was determined standard week and weekend hydrograph for 2017 (**Figure 3 (a)** and **(b)**) and 2019 (**Figure 4 (a) and (b)**) which were defined as an expected range of values, framed by upper and lower limits of 90% and 10%, respectively. For modelling purposes, only weekday data were used.



(a) Hydrograph week 2017

(b) Hydrograph weekend 2017

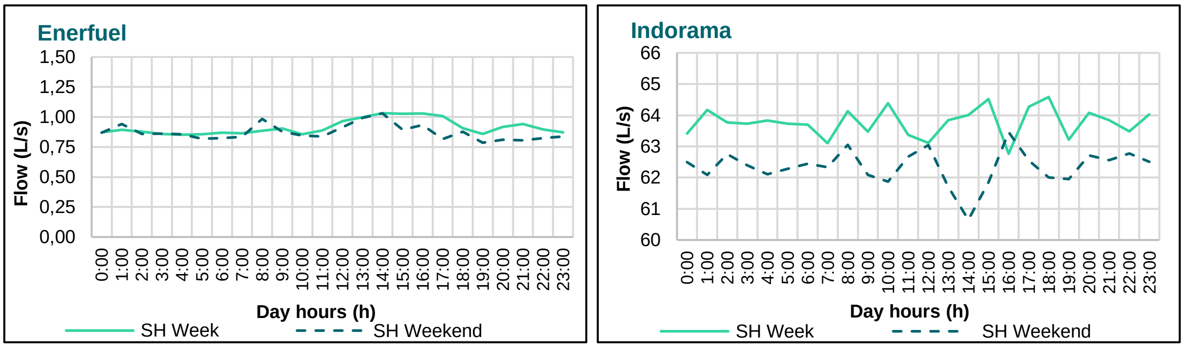
Figure 3 – Standard hydrograph week (a) and weekend (b) 2017 and 90% and 10% percentiles - Ribeira de Moinhos WWTP.



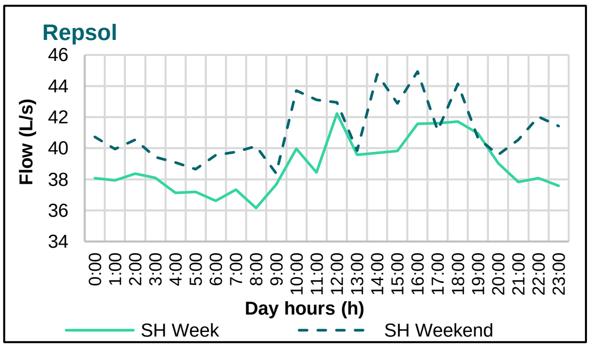
(a) Hydrograph week 2019 **(b)** Hydrograph weekend 2019

Figure 4 – Standard week (a) and weekend (b) hydrograph of 2019 and 90% and 10% percentiles - Ribeira de Moinhos WWTP.

The standard 2019 hydrographs from the Indorama, Repsol and Enerfuel industries were obtained for which instantaneous flow data were also available. **Figure 5 (a)**, **(b)** and **(c)**.



(a) Hydrograph week and weekend – Enerfuel **(b)** Hydrograph week and weekend – Indorama



(c) Hydrograph week and weekend – Repsol

Figure 5 – Hydrograph week and weekend – Enerfuel (a), Indorama (b) e Repsol (c).

The average daily flow rates in the dry weather system considered for each measuring point of the network are shown in **Table 2**. It should be noted that some wastewater pumping stations and measuring points were deactivated or out of operation during the period considered.

Table 2 – Daily average flow rates (industrial and domestic) affluent to dry weather system.

Measuring point	Affluent daily average flow (L/s)	Affluent daily average flow (L/s)
	Week	**Weekend**
Petrogal	92.04	123.65
Repsol	36.99	46.48
Indorama	60.77	70.94
Air Liquide	0.01*	0.01*
Euroresinas	2.98	3.85
Carbogal (**)	0.00	0.00
E.E. ZIP2 (**)	0.00	0.00
E.E. ZIP3	101.81	123.51
E.E. Palmeiras	0.06	0.00
Enerfuel	0.85	0.85
E.E. Santo André	21.21	20.63
E.E. RESIM	0.10*	0.10*
C.M. Santiago do Cacém	12.40	15.56
C.M. Sines	20.25*	20.25*

(*) Estimated value from monthly data of 2018; (**) Lifting stations currently disabled or non-functioning.

In order to calibrate and validate the model in wet weather, nine precipitation events recorded by the ZIL2 precipitation gauge were considered relevant during 2017. (**Figure 6**).

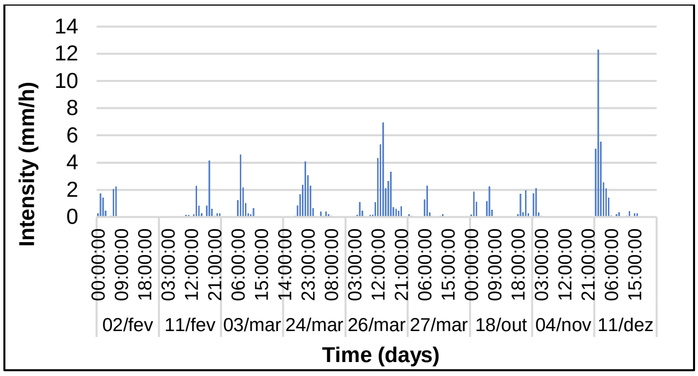


Figure 6 – Hourly precipitation intensity recorded in weather station ZIL2 for different events of 2017.

Scenario type A

In this scenario, for the purpose of flow storage, we consider storages in three different locations: two existing storages located along the system, namely the Santo André basin, with a useful volume of 5 000 m^3, the retention basin located with E.E. ZIP3, with a usable capacity of 7 000 m^3, and a new proposed basin next to the Ribeira de Moinhos WWTP.

Scenario type B

For simulation purposes, in this scenario, several precipitation events were considered with an annual frequency of 1, 5 and 10 times (F1, F5 and F10), **Table 3**, obtained based on the analysis of the precipitation regime in the Lisbon region referring to 18 full hydrological years (Ferreira, 2006).

Table 3 – Precipitation considered for the simulation.

Event Frequency (-)	Frequency (-)	I (intensity) (mm/h)	D (duration) (h)
F1	1x/year	13.9	4.0
F5	5x/year	8.0	
F10	10x/year	6.3	

The precipitation events used were conservatively considered for the period with the highest dry flow recordings and a constant standard hyetograph was considered for this purpose. The flow entry condition in the proposed additional basin was established through the nominal flow rate of 0.5 m^3/s of Ribeira de Moinhos WWTP.

Results and Discussion

Scenario type A

In this scenario of a stoppage simulation of the Ribeira de Moinhos WWTP, the retention basin receives effluent from Galp Energia Refinery (Petrogal) and the industries Repsol, Indorama, Euroresinas and Air Liquide, whose effluents are received by the E.E. ZIP3. The wastewater from Vila Nova de Santo André flows into the Santo André basin. It was considered that the proposed basin near the Ribeira de Moinhos WWTP would receive the effluents from the remaining contributors, Santiago do Cacém, Sines and zone 1 (Enerfuel).

- **Retention basin**

a) **b)**

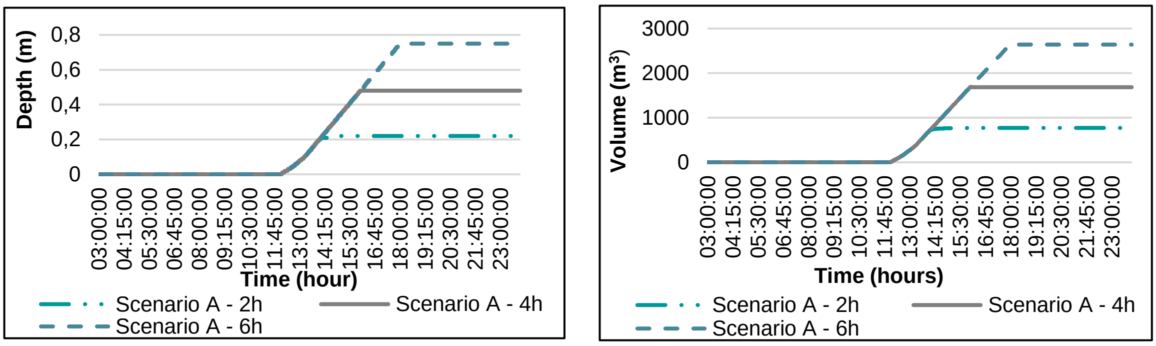


Figure 7 – Water depth (m) (a) and volume (b) (m^3) simulated in the system retention basin - Scenario A.

Figure 7 (a) and **(b)** shows that for a 2h WWTP interruption period, a depth of 0.22 m is reached and a volume of approximately 772 m^3 is accommodated in the basin. For 4h and 6h stopping, the simulated depth and volume were 0.48 m and 1 685 m^3, and 0.75 m and 2 642 m^3, respectively. For simulated downtime, the basin's maximum depth and volume (2.2 m and 7 000 m^3) were not exceeded.

- **Santo André basin**

a) **b)**

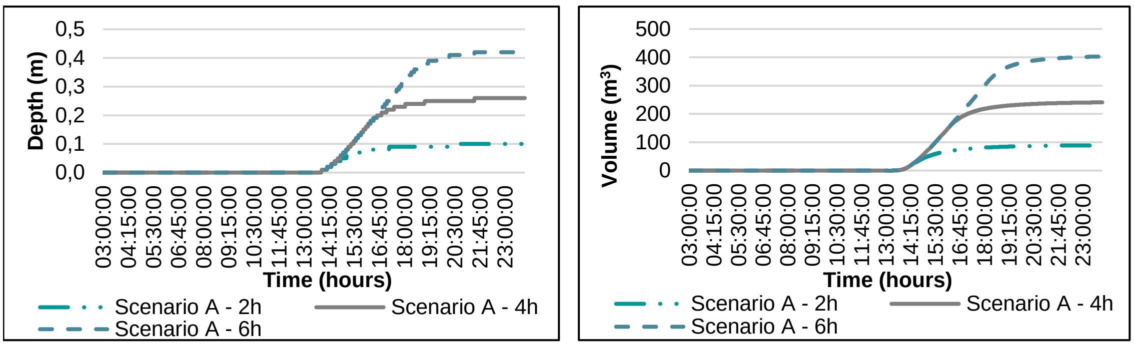


Figure 8 – Depth of water (m) (a) and volume (b) (m^3) simulated in Santo André basin - Scenario A.

Figure 8 (a) and **(b)** shows that for a 2h WWTP interruption period, a depth of 0.1 m and a volume of 89 m^3 are achieved. For the 4h and 6h stopping periods, the simulated depth and volume were 0.26 m and 239 m^3, and 0.42 m and 401 m^3, respectively. It should be noted that for the simulated downtime the basin's maximum depth and volume (4.2 m and 5 000 m^3) were not exceeded.

- **Proposed additional basin next to Ribeira de Moinhos WWTP**

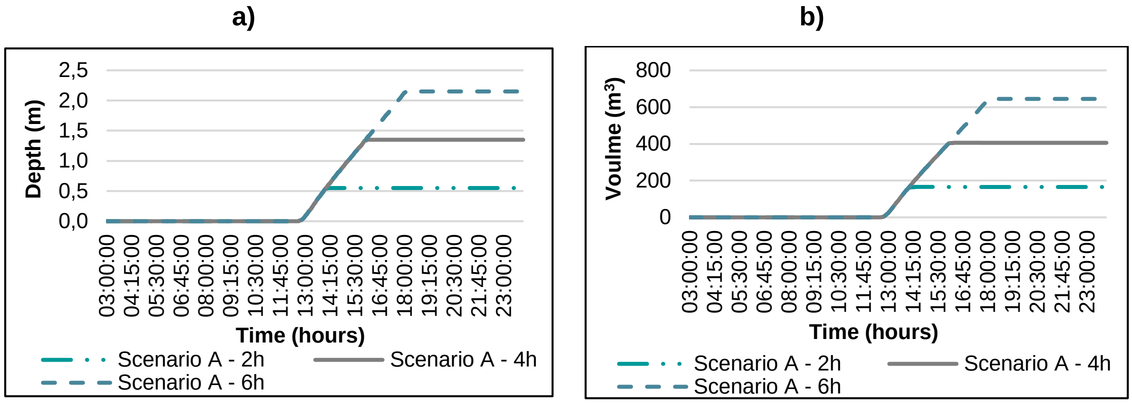


Figure 9 – Depth of water (m) (a) and volume (b) (m^3) simulated in the proposed basin at the WWTP - Scenario A.

Figure 9 (a) and **(b)** shows that the proposed additional basin water depths achieved for the 2h, 4h and 6h interruption periods were 0.55 m, 1.35 m and 2.15 m for storage volume of 165 m^3, 406 m^3 and 645 m^3, respectively.

Scenario type B

The formulation of this scenario allows estimating the period that the Ribeira de Moinhos WWTP could remain without discharging, in wet weather, in the presence of an end-of-line storage.

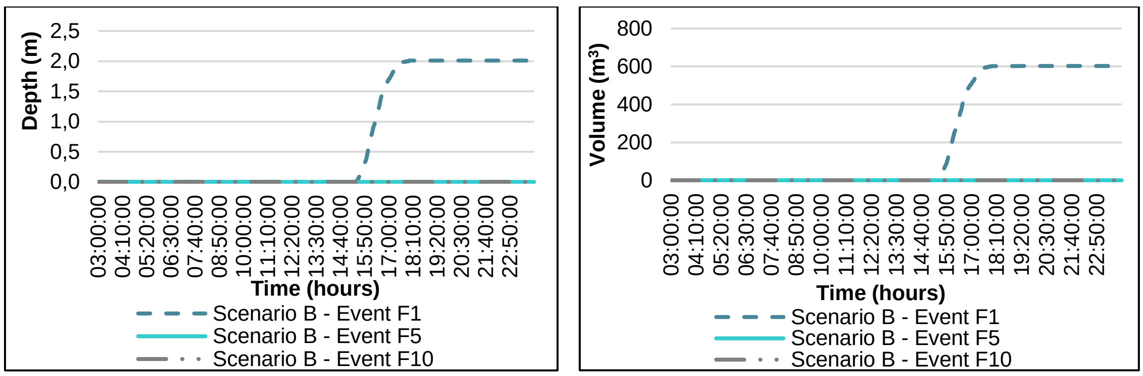


Figure 10 – Volume occupied (m^3) in the proposed basin near the WWTP - Scenario B (Events F1, F5 and F10).

In scenario type B, **Figure 10**, it was found that with the occurrence of event F1, intensity 13.9 mm/h, it was necessary to store a volume of 603 m^3 in the proposed basin near the WWTP, reaching an depth of 2.01 m. For the remaining events, F5 and F10, with intensities 8.0 mm/h and 6.3 mm/h, it was verified that it was not necessary to store effluent in the basin.

Conclusions

For monitoring purposes, in respect to the criteria and according to the analysis performed, the installation of additional gauges was not considered deemed necessary. For flow measurement, it was considered necessary to install three additional depth and flow velocity gauges at the following locations:

downstream of the Intermediate Meeting Chamber (Barbuda), downstream of the E.E. of Santo André (next to CT2) and downstream of the General Meeting Chamber (CRG).

Despite the lack of field information, from the calibration and validation processes it was possible to reproduce the system behaviour, with associated errors staying within admissible limits. It was observed that, under wet weather, the errors associated with the simulated results compared to the measured ones were more evident. This may be due to the use of flow measurements from different years and the uncertainty associated with the spatial variability of precipitation, since only one precipitation gauge's (ZIL2) rainfall records were used.

In the simulated scenarios it was concluded that, in case of interruption of the Ribeira de Moinhos WWTP operation during 2h, 4h and 6h, in dry weather, the existing storages throughout the system, retention basin near the E.E. ZIP3 and Santo André basin, have the capacity to accommodate the effluents they receive. The retention basin reached about 38% of its capacity for a 6h WWTP interruption and the Santo André basin approximately 8% for the same period. For this scenario, it was also found that the proposed additional basin near the end-of-line storage (WWTP) should have a useful storage volume of about 700 m^3 for a maximum WWTP interruption period of 6h.

In scenario type B, it was found that in the occurrence of event F1, intensity 13.9 mm/h, it was necessary to store a volume of 603 m^3 in the proposed additional basin. In the remaining events, F5 and F10, of intensities 8.0 mm/h and 6.3 mm/h, it was not necessary to store effluent in the basin given the performance optimization of the other two storages. Therefore, based on the simulated results, it was concluded that, for the occurrence of more significant events, the proposed additional basin allows to store a considerable effluent volume, avoiding the overflows. From a practical point of view, and considering that it will be difficult to optimally operate the valves, it is believed that the additional basin near the WWTP should have at least 1800 m^3, corresponding to a downtime of about two hours, adequate time for warning and valve actuation.

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