STRATEGIES FOR IMPROVING AND OPTIMIZING THE PERFORMANCE OF COMBINED SEWER SYSTEMS

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ABSTRACT

Urban drainage systems in Europe are mostly combined or mixed. The problem associated with this typology of systems is related to the existence of a greater affluence of surface runoff to the network, along with the increase of infiltrations in periods of higher rainfall, often resulting in overloading of the WWTP and, consequently, in combined sewers overflows directly into the receiving environment. The occurrence of frequent discharges is an environmental problem as far as it leads to the degradation of the quality of the receiving environment. Currently, increasing environmental concern and the need to comply with quality parameters have led to the development of different strategies that are alternative to end-of-pipe treatment, such as base solutions, interception of flows and the expansion of the system's storage capacity. The expansion of storage capacity by means of the construction of retention tanks allows to reduce the frequency and volume of overflows, being that in the last decades it has become common practice in countries of North and Central Europe, such as Germany, Holland and Denmark. The main objective of this dissertation is to present the different techniques currently used for the improvement of combined systems, with a main focus on the expansion of the system capacity by the implantation of storage basins. In this way, methodologies of sizing and design of storage structures will be presented.

Key-words: combined sewers, combined sewers overflows, storage basins, urban drainage

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1. INTRODUCTION

The urban growth observed in the last decades has resulted in an exacerbated increase of waterproofing and urban land occupation, reducing superficial natural flows and significantly increasing floodwaters. This phenomenon, coupled with the aging and poor functioning of existing drainage systems, results in the occurrence of excess flow discharges to the receiving medium. According to FIELD *et al*. (2004), the United States Environmental Protection Agency (EPA) estimates that there are between 23,000 and 75,000 overflows discharges per year in the United States, which translates into a discharge of about 4 million cubic meters of polluted overflows to the receiving medium. The occurrence of frequent discharges of domestic wastewater is an environmental and public health problem, as it leads to degradation of the quality of water resources. In Portugal and in other southern European countries, this problem is particularly relevant due to the fact that several watercourses dry up during the dry season.

Currently, growing environmental concern and the need to comply with water quality legislation has led to the development and implementation of strategies based on structural and non-structural measures with the ultimate goal of eradicating the discharge of polluted overflows into the receiver medium. Initially, the construction of separate systems and the expansion of the WWTP were measures that were often considered. However, excessive costs and inefficiency due to undue influences in the system led to the search for new solutions. Thus, current trends are based on the adoption of four types of solutions: source control solutions, structural solutions to expand system storage capacity, real-time control solutions and end-of-pipe treatment solutions.

In the recent decades, the construction of overflows storage structures has become standard practice in European countries, such as Germany, the Netherlands and Denmark, and various methods have been developed for determining their volume. In the national context, the city of Lisbon faces particularly complex challenges to manage and control overflows discharges. Facing this problem, in 2016, under the context of Plano Geral de Drenagem de Lisboa (PGDL), several solutions were developed with the aim of improving the flow conditions and reducing the risk of flooding in the Alcântara Basin, like the construction of a tunnel that will allow the diversion of the tributary flow of the low zone of Alcântara, for discharge in Santa Apolónia. At the same time, and taking advantage of the planned contract, it was considered the construction of a 16 000 m^3 storage basin with effluent pretreatment.

2. GENERAL CONCEPTS

Storage basins are generally constituted by the entrance, the retention chamber, the flow control devices and the telemetry system. Figure 1 shows a schematic representation of a storage basin with the identification of some of its main elements.

Storage structures can be classified according to their main function or according to their position relative to the drainage network. Concerning their main function in the system, basins can be classified in anti-pollution basins, which consist in structures designed to avoid the discharge of polluted flows to the receiving medium, and which are usually located in the final part of the tributary basin; in anti-flood basins, which consist in structures designed to prevent flooding during the overload of the drainage system, and which are usually located in the upper or middle parts of the tributary basin; and in mixed basins, which consist in structures whose main objective is to prevent flooding, yet containing regulatory elements that allow the control of discharges of polluted effluents. As regards classification according to the relative position in the drainage network, the basins can be classified in online basins, off-line basins or combined basins. Online storage basins are structures that are in alignment with the influent drainage collector, intercepting it, and allowing all tributary flow through the structure. Off-line basins consist in structures implemented parallel to the inflow collector, and for that reason not all the flow enters the structure. Combined basins consist in a set of sequentially coupled compartments, in which the first compartment is typically on- line.

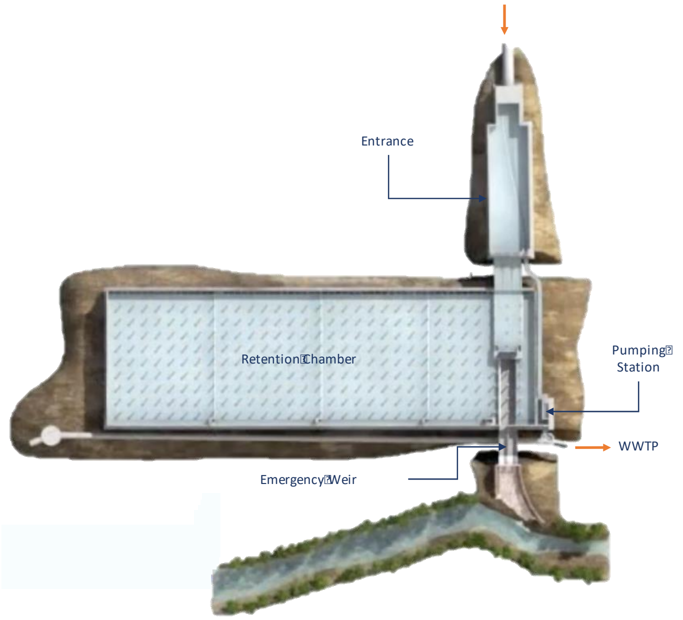

Figure 1 – Schematic representation of a storage basin.

Currently, in Portugal, the process of designing storage basins is still poorly structured, and for that reason there is a need to establish coherent criteria to support the design process, in order to meet the established environmental objectives. In this way, this chapter sets out a series of technical criteria and specifications, listing not only the various elements that make up the structure, but also the associated constructive aspects. Choosing the location of the storage structure is one of the most complex operations in the design process due to the consequences that its implantation entails at the urban and environmental level. Among the several constraints that affect the choice of location, the availability of sufficient space, urban conditioning, the proximity of the receiving medium and the drainage network configuration are the most important ones. The locations of storage basins are dependent on their purpose, i.e. whether they are structures designed for anti-flood or anti-pollution purposes. Typically, and generally, there are two locations for storage structures: at the top of the tributary basin and immediately upstream of the treatment plant, at the end of the basin. Storage basins designed for flood control are generally deployed in the upper part of the river basin, and it is preferable to construct several smaller basins instead of a single larger basin. When the goal of the storage basin is to control pollution in the receiving medium, it is common to implant the structures at the end of the tributary basin, more specifically at the intersection point between the drainage network and the smaller diameter interceptor to the WWTP.

After defining the place to implement the structure, it is necessary to define its geometry taking into account some criteria such as the maximum water level, the depth of the structure and the required area. The maximum level of water is dependent on the drainage network upstream of it and its establishment must ensure that, when the retention chamber reaches its maximum capacity, it is possible to exploit the capacity of the upstream collectors without extravasation. In the design process, particularly for anti-pollution and pretreatment structures, minimum depths of 4 meters are recommended, since the efficiency of the structure increases with its depth. However, the definition of the depth of the structure should take into account the groundwater levels and associated excavation and construction costs, being that, wherever is possible, the chosen design should allow the emptying by gravity , given the costs associated with pumping operations (MAGRAMA, 2014). .

The geometry of the structures may be rectangular, circular or irregular. If a rectangular geometry is chosen, the length should preferably be 1.5 to 2 times the width. In structures with intermediate volumes and large depths it is preferable to adopt a circular geometry, although, for the same volume of storage, it requires larger dimensions than rectangular structures. Irregular geometries should be avoided due to the high operating costs, being specifically indicated for open basins, since they allow a better aesthetic framing and integration in the urban environment

3. METHODOLOGIES FOR SIZING STORAGE BASINS

3.1. Introductory Notes

The construction of storage structures is an effective measure for limiting and controlling overflows of combined systems. The methodology for sizing storage basins can vary according to its main objective, i.e. if its objective is to allow a minimum level of treatment (primary treatment), whether it is to allow first-flush capture or if is to reduce the annual number of direct discharges of overflows. There are several design methods, being the most used ones the Critical Precipitation Method, the Simplified Method, the Hydraulic Load Criterion and the Dutch Method.

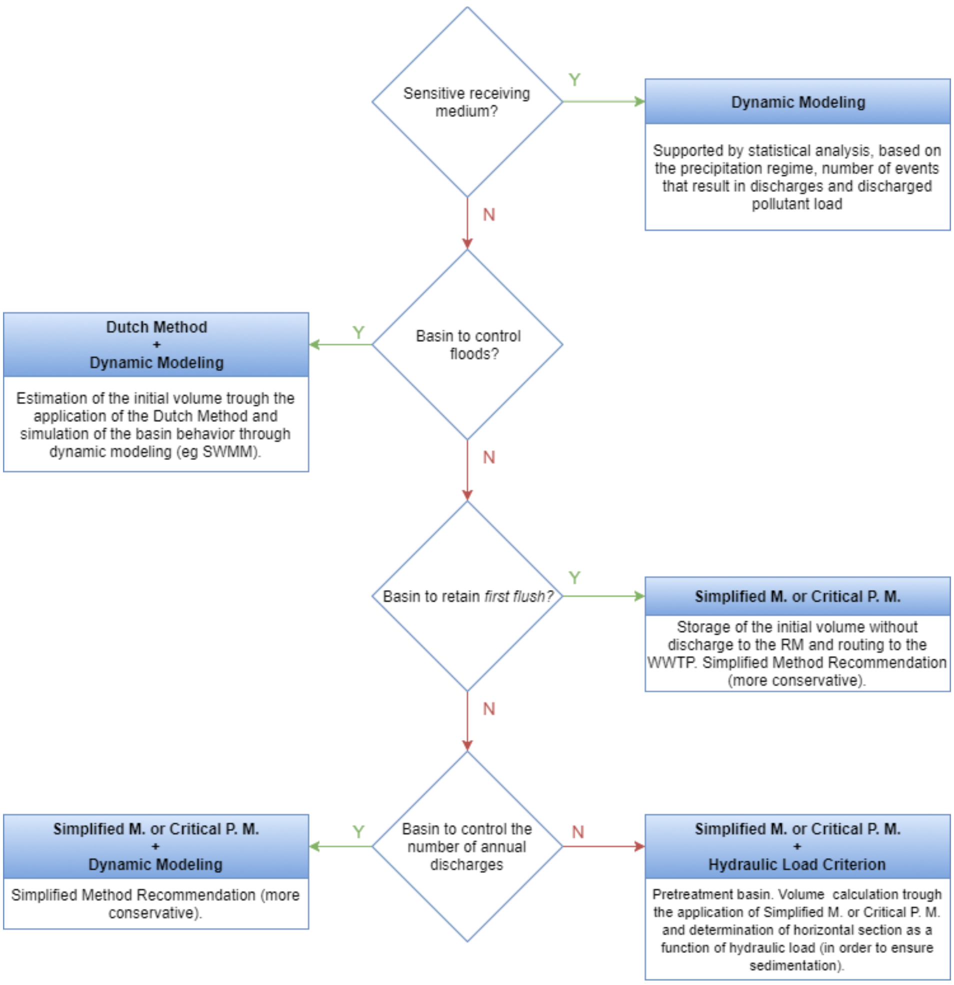

Figure 2 - Flowchart of the designing processes according to the purpose of the storage basins.

According to the flowchart in Figure 2, to size a flood control basin, it is first recommended to apply the Dutch Method to estimate the initial volume of the basin, and then to perform dynamic simulations to evaluate the structure behavior in different scenarios. To design an antipollution basin it is necessary to apply the Critical Precipitation or Simplified Methods, according to the specific objective of the basin. For basins with concentration times less than 20 minutes, the objective is typically the retention of the initial effluent therefore, the application Critical Precipitation Method or the Simplified Method is recommended. The latter allows obtaining larger volumes and for that reason is considered more conservative. For drainage basins where first flush does not occur, but where the frequency of direct discharges to the receiving medium needs to be controlled, in addition to the application of the above-mentioned methods, it is recommended the performance of dynamic simulations in order to evaluate the behavior of the structure for different pluviometric regimes. Anti-pollution storage basins that do not aim to retain the first flush or limit the number of overflow discharges are designed to provide pre-treatment for the stored effluent and therefore, in addition to the Critical Precipitation Method or the Simplified Method, the Hydraulic Load Criterion should be applied in order to determine the horizontal section and height of the basin.

3.2. Critical Precipitation Method

The Critical Precipitation Method was developed by Krauth during a study on the operation of the Stuttgart-Busnau combined system in Germany. The study was part of an international cooperation project in which it was decided to build storage basins to ensure the protection of Lake Constance (located between Germany, Austria and Switzerland). This particular study had a fundamental contribution not only on the demonstration of the influence that the processes of resuspension and transport of sedimented material in the collectors have on the discharged pollutant load, but also on the importance of storage structures for the purpose of controlling that same discharges (MINISTÈRE DE L'AGRICULTURE, 1988).

Through the study, it was observed that during the night period and diurnal periods with lower affluence, the decantable substances accumulated inside the collectors and that some of these substances were not dragged during the periods of greater affluence. It was also observed that precipitations with an average intensity higher than 10 l/(s.ha) produced a drag and considerable cleaning action of fine substances deposited inside the collectors, and it was verified that in the initial period of the hydrograph there was a significant flow of pollutants (BOD_5 and TSS). This initial flow, called first-flush, showed a rapid decrease, being practically imperceptible after 30 minutes of the beginning of the hydrograph. From the analysis of the suspended solids, it was estimated that 78% came from the sedimentated material in the collectors and the remaining 22% came directly from the drainage basin (MINISTÈRE DE L'AGRICULTURE, 1988). Although the existence of first-flush effect is not yet unanimous in the scientific community, its study proves to be an important aid tool in the control of overflows discharges. Thus, when storage basins have as main objective the retention of the first flush, the Critical Precipitation Method must be adopted to determine its storage volume.

The Critical Precipitation Method is based on the use of abacuses and basic hydraulic criteria to size storage structures that retain, during a certain period of time, the flow caused by a precipitation event with a certain critical intensity. The critical precipitation intensity (Ic) is the fundamental parameter for which the system is dimensioned, since only when precipitations with an average intensity exceeding the critical intensity occur, there is possibility of direct discharges to the receiving medium. Thus, the greater the value of the critical precipitation intensity, the greater the retention capacity of the system to be dimensioned.

As noted above, the specific storage volume of the storage basin, i.e. the volume per unit area of the drainage basin, is determined by querying an abacus whose input parameters are the critical precipitation intensity (defined *a priori*) and the specific flow admitted downstream of the WWTP (I_{jus}), calculated through expression 2.1:

$$I_{jus} = \frac{Q_t - (Q_{tsp} + Q_{rS} + \Sigma Q_{t,m})}{C \times A} = \frac{Q_{jus}}{A_{red}} \quad (3.1)$$

In which:

I_{jus}	–	specific rainwater flow that is admitted to pass to the WWTP (l/(ha.s));
Q_{jus}	–	part of the critical rainwater flow that is allowed to pass downstream of the storage structure to the WWTP (l/s);
Q_t	–	maximum flow that is allowed to pass downstream of the storage structure (l/s);
Q_{tsp}	–	peak flow in dry weather (including portions from separate systems, but excluding the portions from discharge basin served by other storage structures) (l/s);
Q_{rS}	–	rainwater flow that, due to improper connections and increased infiltration, enters through the separate networks of domestic wastewater installed upstream, during wet weather periods (l/s);
$\Sigma Q_{t,m}$	–	sum of flows that are allowed to pass downstream of storage structures located upstream of the drainage basin considered (l/s);
A	–	area of the drainage basin upstream of the storage structure (without regard to the drainage basin areas of other storage structures) (ha);
C	–	coefficient of the method (-);
A_{red}	–	reduced area of the drainage basin (ha).

The storage basin design process by applying the Critical Precipitation Method, must meet a number of criteria and hydraulic checks that, by paging limitation issues is not listed in this document. Therefore, it is advisable to consult ATV-A128 (1992), in which there is a detailed explanation of the method.

3.3. Simplified Method

The Simplified Method is used to size storage structures by consulting abacuses, and is particularly suitable for designing storage basins whose main objective is to reduce the number of excess flow discharges to the receiving medium. Pollution caused by discharges of overflows depends on numerous parameters, including the duration and frequency of discharges and the type and concentration of pollutants. In a simplified way, the method assumes the annual pollutant load discharged in terms of Chemical Oxygen Demand (COD) as a parameter indicative of pollution. It should also be noted that due to the difficulty of predicting pollutant loads in the flow for isolated precipitations, the Simplified Method is based on annual average flows and on average annual pollutant concentrations in dry weather and rainy wet weather.

During wet weather, flows from combined systems which are discharged to the receiving medium through the weirs and through the treatment plant have, respectively, higher and lower concentrations than the rainwater affluent to the system. Thus, the Simplified Method establishes as a sizing criterion that, in average year and in combined drainage systems, the annual pollutant load discharged to the receiving medium must be lower than the COD load yearly transported by the rainwater to the interior of the collection network. Thus, the determination of the storage volume required upstream of each sub-basin is based on the verification of the following balance, expressed in COD, in average year (ATV-A128, 1992):

$$PL_0 + PL_{et} \leq PL_r \tag{3.2}$$

In which:

- PL_0 – annual pollutant load, in COD, discharged to the receiving medium by direct discharges of combined overflows(kg);
- PL_{et} – annual pollutant load, in COD, of the runoff portion discharged to the receiving medium after treatment at the WWTP (kg);
- PL_r – annual pollutant load, in COD, of the rainfall affluent to the combined system (kg).

Equation 3.2 allows determining the maximum permissible relation between the annual volume of overflow discharge and the annual volume of useful precipitation. The lower the ratio, known as the permissible rate of overflow discharge, the higher the storage volume to be require to the system. The permissible overflow discharge rate (e_0) is defined as the quotient of the annual average volume of direct discharges to the medium and the average annual volume of rainwater affluent to the drainage system, and can be calculated by the following expression:

$$e_0 \leq \frac{c_r - c_{et}}{c_{co} - c_{et}} \tag{3.3}$$

In which:

- e_0 – permissible rate of overflow discharges (m^3);
- c_r – average COD concentration in rainfall (mg/l);
- c_{et} – average COD concentration in the WWTP rainwater effluent during wet weather (mg/l);
- c_{co} – average theoretical COD concentration of combined overflows discharges (mg/l).

Similar to the previous method, the determination of the specific storage volume is performed by consulting an abacus, whose input parameters are the discharge rate of overflows (e_0) and the specific flow admitted to the WWTP (q_{r24}), which can be calculated by applying the following formula:

$$q_{r24} = \frac{Q_{r24}}{A_i} = \frac{Q_t - (Q_{ts24} + Q_{rS})}{A_i} \tag{3.4}$$

In which:

- q_{r24} – specific average rainwater flow that is admitted to the WWTP (l/(s.ha));
- Q_{r24} – average rainwater flow that is admitted to the WWTP (l/s);
- A_i – impervious area of the drainage basin (ha);
- Q_t – maximum flow that is allowed to pass downstream of the drainage sub-basin to the WWTP (l/s);

Q_{ts24} – average dry weather flow (including infiltration flow rate and flow rate from separative systems of domestic wastewater upstream) (l/s);

Q_{rS} – average infiltration rate, in wet weather, from separative systems of domestic wastewater (l/s).

The determination of the theoretical average COD concentration of overflows discharges (C_{co}), is performed through the application of several formulas and consultation of abacuses, which, for the purposes of synthesis, will not be presented in this document. In this way, once again, it is advisable to consult document ATV-A128 (1992) for further explanations.

3.4. Hydraulic Load Criterion

The sedimentation phenomenon that occurs due to the retention of stored overflows can be considered as part of the pretreatment process, therefore, many storage basins are currently dimensioned in order to operate with this dual functionality (LAGER, 1974). The solids removal by sedimentation can be estimated by continuous modeling processes, considering as input parameters the distribution of particle velocities and the inflow to the basin (DRISCOLL, 1986), however, there are simplified sizing methods and criteria that guarantees the flow pretreatment. Similarly to the methods presented above, the German standard ATV-A128 (1992) establishes a sizing criterion for storage basins with dual functionality (storage and pretreatment), the Hydraulic Load Criterion, based on the Critical Precipitation Method design criteria and the hydraulic charge criterion (H_b). According to MICHELBACH & WEIß (1996), the establishment of an average hydraulic load of 10 $m^3/m^2/h$, allows a removal efficiency of 80% of the suspended solids. However, the determination of the required retention time and, consequently, the removal efficiency of this type of structures, is a complex process, being dependent not only on the concentration of pollutants and the inflow, but also on the duration and intensity of the pluviometric event

Typically, the German clarifying type storage structures are compartmented, i.e. they are constituted by two or more retention chambers. The compartmentalization of the structure, although it entails higher initial costs, will result in lower operating and maintenance costs, since, for lower rainfall events, only the first compartments will be used, and there for, there is no need for the others to operate (FIELD, et al., 2004). From the point of view of environmental performance, compartmentalization is also beneficial since the concentration of suspended solids decreases over the series of compartments, being the flow stored in the last compartment, which will be directly discharged to the medium in case of system overload, the one with the lowest TSS concentration.

Firstly, the Critical or Simplified Precipitation Methods should be applied to determine the volume of the storage structure. Subsequently, the hydraulic load criterion for determining the horizontal section of the basin should be applied using the following expression:

$$A_h = \frac{Q_{crit}}{H_b} = \frac{Q_{crit}}{10} \tag{3.4}$$

In which:

Q_{crit} – critical combined flow affluent to the storage basin (m^3/h);

A_h – horizontal section of the storage basin (m^2);

H_b – storage basin hydraulic load (m/h).

Once the values of the volume and horizontal section of the structure have been determined, it is then possible to determine its height. It should be noted that the adoption of a value of 10 $m^3/m^2/h$ for the hydraulic load criterion corresponds to a critical precipitation intensity in the order of 15 l / (s.ha), so this value should be considered when the calculation of critical rainfall by applying the Methods of Critical and Simplified Precipitation (ATV-A128, 1992).

3.5. Dutch Method

The application of the Dutch Method allows an initial estimation of the volume required to design an anti-flood basin, being its conjugation with dynamic simulation models always necessary to evaluate the behavior of the the structure. According to MATOS (2006), the Dutch method is based on the knowledge of the intensity-duration-frequency curves of the area under study, and is particularly suitable in the pre-dimensioning phase of the storage basin. The application of this methodology allows the necessary volume calculation to store the tributary flow resulting from critical precipitation, return period T, in order to guarantee a constant flow q, corresponding to the natural state of the basin in a pre-urbanization situation. In this way, the specific effluent flow rate can be calculated using the following formula:

$$q_s = \left[\frac{q}{C\,A}\right] \times 6 \times 10^{-3} \tag{3.6}$$

In which:

q_s – specific effluent flow (mm/min);
A – affluent basin area (ha);
C – coefficient (-);
q – flow rate of the natural basin (l/s).

The minimum storage volume required can be calculated by applying the following expression:

$$V = 10\,A\,C\left[\frac{-b\,q_s}{1+b}\right]\left[\frac{q_s}{a\,(1+b)}\right]^{1/b} \tag{3.7}$$

In which:

V – minimum storage volume required (m^3);
A – affluent basin area (ha);
C – coefficient (-);
a,b – parameters of the intensity-duration-frequency curve, for a given return period (-);
q_s – specific effluent flow (flow per unit of waterproofed area), considered constant (l/s).

4. CONCLUSION

The construction of storage basins is a strategy for the improvement of combined systems, since it reduces the discharge of overflows directly to the receiving environment, contributing to the protection of the quality of water resources. Different methods ans criteria can be used for sizing the storage structures, such as the Critical Precipitation Method, the Simplified Method and the Hydraulic Load Criterion. All methods use abacuses and/or empirical formulas to proceed with the dimensioning of the structures, based on a specific dimensioning criterion. Although all the methods are empirical and with relatively easy to use, they present some limitations that must be considered when applying them. In all methods, the sizing process does not consider the specific condition of the receiving medium and although the Critical Precipitation Method and the Simplified Method take into account a quality parameter (BOD_5 in the Critical Precipitation Method and COD in the Simplified Method), they can only be used if there is no special protection applied to the receiving medium. Thus, for situations in which the receiving medium is considered sensitive, it is advisable to use mathematical simulation models, which integrate other relevant parameters.

Regarding the design of storage basins, and given the complexity of their operation, it is important to establish a constructive methodology based on generalist guiding principles, in order to standardize and support the process.

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