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Assessing intermittent saline inflows in urban water systems

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ABSTRACT

Urban water drainage systems' primary function is to transport sanitary or stormwater. The intrusion of saline waters has recognized detrimental effects. Especially in coastal areas, saline inflows can compromise performance by increasing the risk of untreated discharges, weakening the structural condition of concrete or metallic components, reducing the effectiveness of wastewater treatment processes and limiting the potential reuse for irrigation. Performance deterioration can be prevented by an early assessment of exposure to saline water, followed by timely actions to control its causes and consequences. The paper describes a procedure for diagnosing undue saline inflows. The procedure is based on the determination of saline inflow's magnitude, acceptance levels, and contribution to the system's performance. Contextual factors and performance indicators, and their reference values, are selected for the assessment. Options to address the problem are proposed, depending on the results. These options can relate to organizational, operational, and structural actions. Application to a case study allowed to validate the method and discuss the results. Here, saline volumes entering the system are quite relevant (almost 30%), posing problems regarding corrosion, treatment plant operation and significant concrete exposure to intermittent saline waters.

Key words: assessment, saline water, sewers, undue inflow

HIGHLIGHTS

- Saline inflows affect performance, risk and cost in urban drainage systems.
- Paper proposes diagnosing their magnitude, acceptance levels and mitigation actions.
- Addresses hydraulic and environmental issues, structural condition of concrete and metallic components, wastewater treatment effectiveness and reuse for irrigation.
- Aligns with infrastructure asset management.
- Considers system upstream, coastal, surface and ground waters.

INTRODUCTION

The primary function of urban water drainage systems is to transport either sanitary or stormwater flows (in separate systems) or both (in combined systems). Separate sanitary systems, besides foul flows, can accommodate some groundwater infiltration, industry, or commercial effluents. Regardless of the type of system, saline waters are not part of the inflows acceptable in sewers.

Seawater can have a salinity corresponding to total dissolved solids (TDS) of above 35 g/L), depending on water temperature and local conditions, while raw wastewater can have a TDS of 0.4 g/L, varying with the upstream sanitary and industrial inflows (EPA 2004; Monte & Albuquerque 2010). The input of a small portion of seawater into the sewers can significantly affect wastewater salinity.

Saline inflows entering sewer systems can come directly from saline coastal waters (Phillips *et al.* 2015) or infiltration of brackish or saline groundwater (Osman *et al.* 2017). These sources are the ones most commonly recognized by water utilities. However, other sources may occur. Domestic or commercial connections, e.g., when brackish water is used in water supply (Tang & Lee 2002), can be an allowed saline water input but still generate deleterious consequences. Industrial activities frequently involve processing steps requiring salt addition, such as the food-processing industry (e.g., meat canning, pickled vegetables, dairy products, and fish processing) and leather industries (Lefebvre & Moletta 2006). Others, such as the petroleum industry, can present a broad range in salinity, from freshwater to three times the salinity of seawater (Diaz *et al.* 2002). Laundry and textile installations using softeners also can input high salinity wastewaters (Lefebvre & Moletta 2006). Road salting for de-icing in colder climates (Osman *et al.* 2017) can also contribute to high salinity inputs to stormwater systems. No previous research was found on the joint consideration of these inputs.

The areas of impact of saline water on wastewater system performance are threefold: disturbances in treatment processes, with efficiency and economic consequences (EPA 2004; Lefebvre & Moletta 2006; Monte & Albuquerque 2010; Flood & Cahoon 2011; Linarić *et al.* 2013); degradation of system components' materials, either concrete or metallic (Flood & Cahoon 2011; CPHEEO 2013; Chalhoub *et al.* 2020); and hydraulic overload, increasing the likelihood of untreated discharges if system components' capacity is exceeded (Flood & Cahoon 2011; Phillips *et al.* 2015). Many utilities are not fully aware of these effects. Others struggle to recognize whether the saline inflows they experience are of concern, given the periodic nature and exposure period, or to recognize the cause of the symptoms they identify, often with a magnitude and overall impact only revealed in the long term. The combination of the several consequences often leads to increased operational and rehabilitation costs and breaches of legal requirements.

Saline inflows are a specific type of undue inflows into sewer systems. Generically, undue inflows can result from: (a) internal causes (e.g. from flow characteristics and material degradation because of aggressiveness of the atmosphere inside the component); (b) external causes (e.g. from groundwater or damages induced by third-parties, as other utilities with underground infrastructures or contractors working in the vicinities); (c) incorrect design, inadequate construction, maintenance or operation (e.g. undue connections between drainage systems or poor manhole construction); or (d) other causes (e.g. equipment obsolesce or modifications in inflow quantity or quality) (Almeida *et al.* 2018). Undue inflow consequences can be recognized in several performance dimensions. Almeida & Cardoso (2010) report potential consequences in six dimensions of performance: (a) hydraulic because of reduction of transport and treatment capacity; (b) structural because of degradation of materials; (c) environmental, because of discharges into receiving environment and treatment efficiency reduction; (d) health and public safety, because of potential increase in flooding risk (with inconvenience to traffic and damages on public or private property) and increased likelihood of contact with polluted waters; (e) economic and financial, because of increased operating and third-party costs; (f) non-compliance issues and reduction of utility performance.

In urban water systems, individual components do not provide a service on their own; analysis needs to consider the behaviour of the system. The causes and symptoms of service failures might not coincide, both in space and time, for instance, when an overflow occurs upstream induced by insufficient capacity downstream because of tidal influence. When addressing the effects of saline inflows on treatment processes, the upstream drainage system and its interconnections with the surrounding surface and ground waters are potential sources to investigate.

Performance deterioration can be prevented by an early assessment of exposure to saline water, followed by timely actions to control its causes and consequences. The paper describes a procedure for diagnosing undue saline inflows proactively. This procedure allows detecting saline inflows, determining their magnitude, and investigating the acceptable levels given the potential consequences. The proposed method is aligned with infrastructure asset management (IAM) (ISO 2014), recognising infrastructures' specific features to assess how overall performance can be affected. Information about predominant processes and causes is essential as the basis to select and plan effective solutions. The rationale of the method adopted is the assessment of potential effects on the utility's performance, both on the service provided and in the infrastructure. The concurrent analysis of causes, symptoms, and consequences, sustained by a set of indicators, is essential for effective action in the system. Therefore, the system is analysed as a whole to promote a comprehensive view of the problem.

METHODS

The proposed method has five steps:

- Analysis and typification of causes and consequences of saline inflows.
- Selection of specific contextual factors, performance indicators and corresponding reference values.
- Identification and assessment of improvement options.
- Selection of the best option.
- Validation in a case study.

Classification of typical causes and consequences supports the selection of an effective course of action since the inflow's mechanisms are understood and acted upon. Generically, the existence of undue inflows is recognized; decision on where to act and what to do, to control or solve the problem, is not always clear, as the identification and location of causes are often unknown. Knowledge of causes allows to identify adequately corrective interventions, locate similar anomalies, and prevent future occurrences (Almeida & Cardoso 2010). Analysis and typification of causes and consequences of saline inflows are undertaken from the literature review and processes analysis.

A tailored set of contextual factors, performance indicators, and reference values is proposed. This set aims to assess the magnitude of saline inflows, prevent their occurrence (by monitoring and acting on their causes and mechanisms), and ensure service quality (by monitoring and controlling their consequences),

To assess the inflow magnitude, whenever it is more closely related to the tide, representative sampling should be ensured. Nyquist's theorem states that a periodic signal (such as tide) must be sampled at twice the highest frequency component of the signal. As spring and neap tides have an approximate frequency of 2/month and daily extreme and average tides of 2/day or 4/day respectively, data on tides ought to be taken at least 8/day (every 3 h) ensuring that tidal cycles (daily and monthly) are represented.

The assessment uses performance indicators. These translate the aims of the utility in the medium–long term. Performance indicators are typically expressed as ratios between variables. They contribute to expressing the level of performance in a certain area over a period (Matos *et al.* 2003). By comparing the result of the indicators with pre-set reference values, it is possible to assign a judgment to the result, e.g., good, acceptable, or unsatisfactory (Alegre *et al.* 2017). The reference values for a metric can be set from the literature review, regulations, standards, available assessment frameworks, benchmarking of a representative sample or expert opinion. Indicators include variables that depend on the utilities' activities and decisions. By monitoring the result of the indicators over time, it is possible to assess whether the implemented actions are having the expected impact. The analysis and interpretation of performance indicators' results need to consider the relevant contextual factors. These are contextual aspects independent of management options, such as climate factors, urban occupation, or topography. A judgement cannot be assigned to contextual factors, and therefore reference values are not assigned to them.

Contextual factors and performance indicators can be used for several purposes. These include the diagnosis of the current situation, the selection of the more effective courses of action, the evaluation of the solutions' expected impact and monitoring of the achieved impact in the planning horizon. A more effective diagnosis is expected if the interrelations between causes and consequences are considered (ISO 2014). Overall, one must look at the results assuming the possible explanations for each performance indicator. The complete diagnosis should integrate the analysis of the contextual factors and of the several performance indicators, which are relevant for the problem under analysis (Matos *et al.* 2003).

The diagnosis based on the results for the contextual factors and performance indicators supports the selection of options for the problem under analysis, in this case, saline inflows. Improvement options need to consider the location and the magnitude of the problem, be directed towards its causes and consequences and ensure effectiveness. In some situations, it is challenging to act in the reduction of undue inflows. If salinity derives from the use of water supply with brackish water or salt for deicing roads, in combined sewers, the reduction might prove difficult. When the root cause is related to groundwater or coastal water inflows, the action might be to reduce or avoid the inflows; if originating from an industrial process, pre-treatment allows changing the inflow's characteristics. The magnitude of the consequences of the inflows ought to be considered as well. This allows for a more targeted improvement option. For instance, recurrent exposure of concrete can be reduced by applying some protective coating, if the concrete deterioration is the major problem; however, if treatment is also affected because of increased volumes, another solution needs to be selected.

The selection of the solution needs to consider resources and implementation opportunities. Short-term resolution of the root causes is often not workable, since these are often many, and costly or geographically dispersed interventions are required. It is possible to intervene in localized causes to improved performance, and gradually implement good practices, that progressively contribute to system sustainability (Almeida *et al.* 2018). Options to deal with undue inflows can be classified as organizational, operational, and structural. The first includes management options and is broader in their application. Standardization on asset management (ISO 2014) is a starting point for identifying organizational aspects that promote sustainability, alignment within the internal structures of the organization, consideration of stakeholders' needs and expectations, and data management. Operational options relate to operation and maintenance activities, which can range from operation alternatives, inspection and testing techniques, monitoring, cleaning procedures or implementation of temporary bypasses (Almeida & Cardoso 2010; EPA 2015). Infrastructural options relate to physical interventions, as construction works or equipment replacement. These are more limited in their application, focusing on given assets. A selection of rehabilitation procedures is available for renovation, replacement, or component repair. Examples of such procedures are internal lining with continuous pipe or sprayed material, pipe replacement with an open trench or a trenchless technique, repair by injection sealing or cured-in-place patch (Hyman 2005; Almeida & Cardoso 2010; Melchers 2020).

A case study for testing and validating the method was selected. Prerequisites included location by the coastline; availability of data including flow, precipitation and water quality monitoring data, asset registry and component condition data; and previously acknowledged symptoms of saline inflows in the system.

CASE STUDY

Águas do Algarve is the utility responsible for the bulk water supply, wastewater transport, and water and wastewater treatment in the Algarve region. Located on the southern coast of Portugal, the drainage system serves an area of about 5,000 km^2, 311,490 households and has a total sewer length of about 447 km, 192 pumping stations (PS), and 76 WWTP. The region extends from a long coast, well known for the many Atlantic Ocean bathing areas, to an inland mountainous area. The coastal area has a high tourism demand and is also the main receiving water for both rivers and drainage systems. Sewer systems are, on average, over 30 years old. While urbanisation is quite dense on the coast, in innermost areas, urban agglomerates are dispersed, and urban streams are the main receiving waters.

The case study, the Faro-Olhão subsystem (Figure 1) is in the coastal area, being served by one WWTP and 14 PS. Most facilities are close to the Ria Formosa coastal natural park. This subsystem has symptoms of undue saline and excessive stormwater inflows, facing problems of noxious odours, equipment and concrete corrosion (Figure 2, regarding a pumping reservoir, a floodgate and a WWTP concrete wall), and increased energy consumption during high tides. The upstream collection systems, mostly combined and in developed coastal urban areas, are operated by other utilities and connect to Águas do Algarve's separate wastewater system. Most pipes are under tidal influence. Upstream of the WWTP, night flows are rather high, and variation in minimum flows between dry and wet weather seasons is not relevant. The WWTP does not have

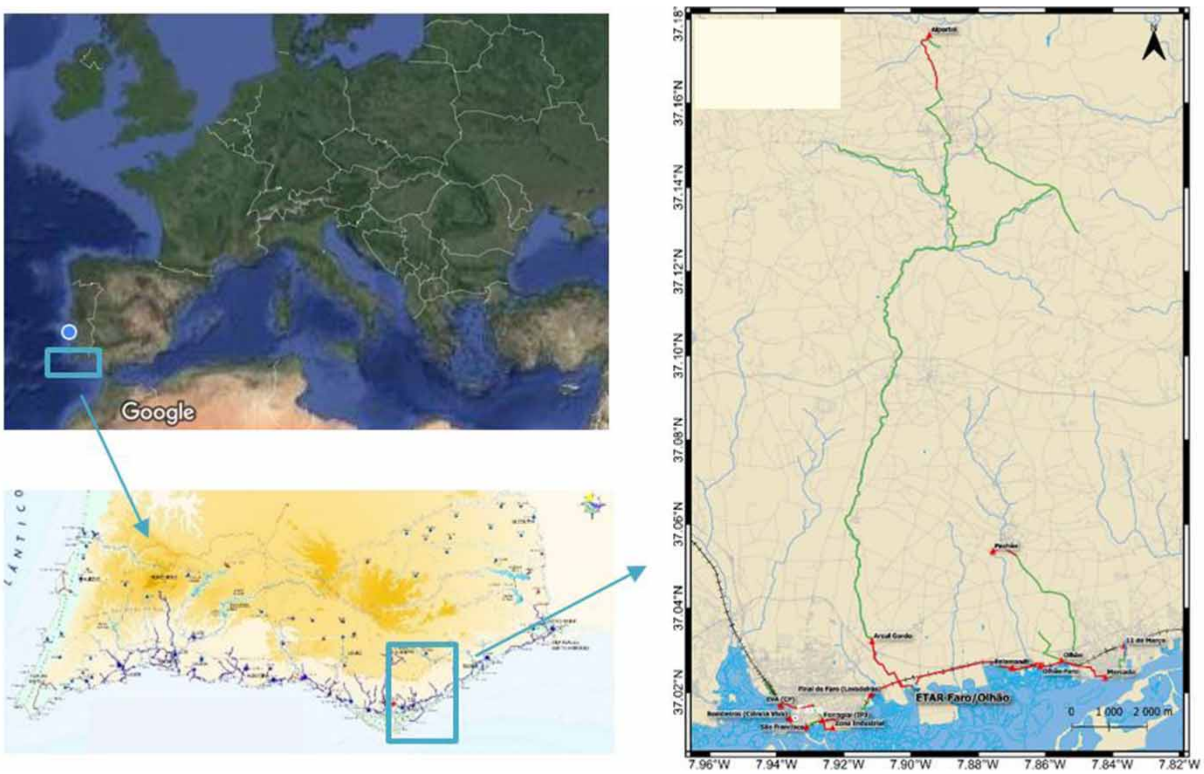

Figure 1 | Águas do Algarve system and Faro-Olhão location.

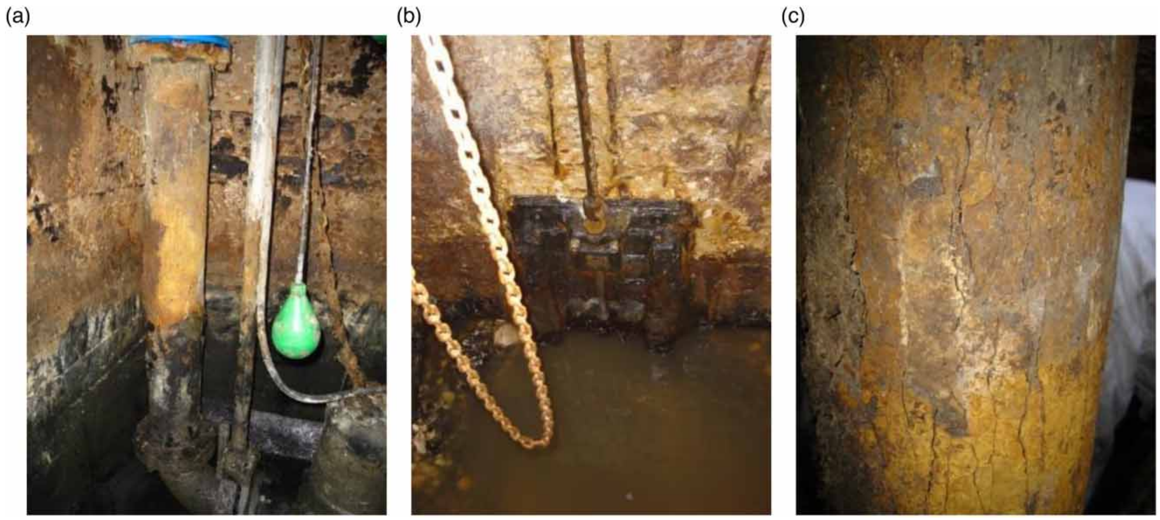

Figure 2 | Corrosion in equipment and concrete components in Águas do Algarve system.

capacity issues or annual non-conformities with the discharge license. However, constraints in sludge biological treatment and sedimentation processes have been experienced. Treated wastewater is not reused for irrigation. Looking at flow and salinity variations together with the tides in the area served by this system, the relation is clear, as shown in Figure 3. Hourly flow and salinity data were registered in the incoming pipe into the WWTP. Tidal heights are recorded and made publicly available by the Portuguese Navy. Four daily records on higher and lower tides are presented in Figure 3.

RESULTS AND DISCUSSION

Analysis and typification of causes and consequences

The most common processes for saline waters inflowing to sewers are groundwater infiltration or direct saline or brackish inflows. These are both undesirable inflows, which might result from infiltration from inland aquifers with high salts concentration or because of saline intrusion of coastal aquifers (van Weert *et al.* 2009). However, saline or brackish waters can also result from allowed water use. These can come from domestic connections, when brackish or seawater is used for public supply, for non-potable uses or cleaning activities in coastal areas (Flood & Cahoon 2011; Tang & Lee 2002; van Weert *et al.* 2009). Some industrial processes also increase water salinity, such as the food, laundry, petroleum, and leather industry areas (Lefebvre & Moletta 2006; Tang & Lee 2002). In colder climates, salt used for deicing roads can be a considerable saline input into sewers (Osman *et al.* 2017).

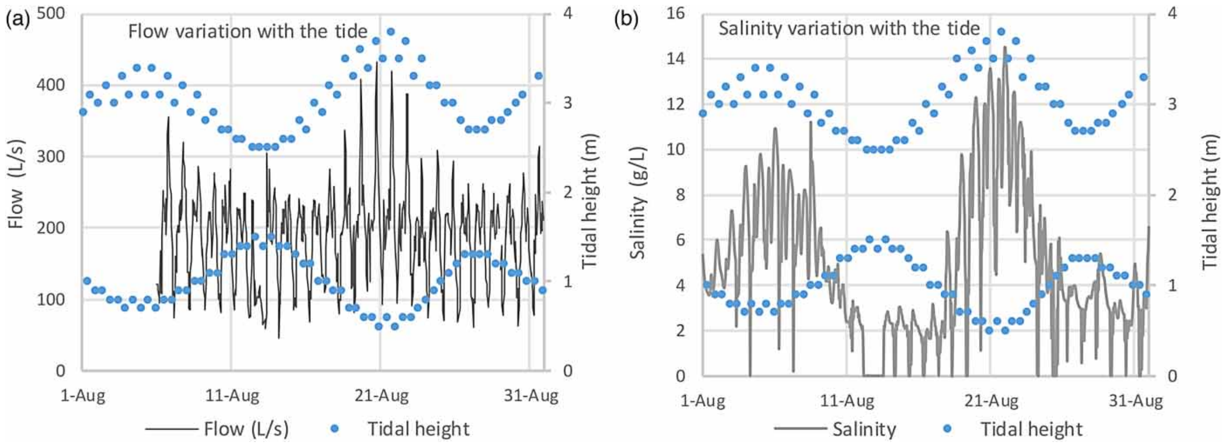

Figure 3 | (a) Flow and tide; (b) salinity and tide in Faro-Olhão WWTP, August 2020 (dry weather).

The effects of high salinity water entering the wastewater systems are diverse. These include the degradation of assets materials (especially in concrete and metals), reduction of treatment processes efficiency, the quality of treated wastewater generated and the quality of sewer sludge. The last two are of concern if water reuse or land application of sludge is envisaged.

Corrosion of materials, because of salinity, can occur both inside or outside of sewers and other system components. Corrosion from the inside is a widely studied problem, resulting from chemical or biochemical deterioration (Mori *et al.* 1991). The corrosion and deterioration from the outside can be because of exposure to a marine environment (Hyman 2005), soil aggressiveness or groundwater contamination (Osman *et al.* 2017). Sewers, which are generally placed between 2 and 3 m below ground, can be regularly submerged in coastal areas and be affected by saline groundwater. Whenever the groundwater elevation exceeds the sewer invert, there is also the potential for ingress of groundwater through joints, cracks, or corroded walls (Osman *et al.* 2017).

High salinity inflows in pumping stations (PS) or wastewater treatment plants (WWTP) can also cause corrosion of concrete and metals. In concrete, corrosion can start in localized air-voids, at the interface with the steel reinforcement. Chlorides also cause the acceleration of the long-term loss of concrete alkali material. These effects are both increased when the quality of the concrete is compromised. This often happens because of poor compaction or existing structural damages in the concrete surface (Melchers 2020) and to humidity, atmospheric oxygen, and reduced concrete coverage of the metallic structures. The intermittence of saturation and drying cycles poses an additional risk. A cyclically humid and dry environment is more problematic because it provides both abundant humidity and oxygen, increasing the concentration of chlorides in the concrete in the long term. Values as low as 0.5% of chloride content in the binder can initiate corrosion (Chalhoub *et al.* 2020). This is a complex issue, and this value depends on several factors. On one hand, the type of reinforcement, the geometry of the bars, the surface structural condition, or the type of concrete. On the other hand, the water temperature, the duration and intermittence of the contact with the saline water, and the deposition and penetration of the marine salts, between others. When reinforced concrete is adequately designed and built, it can endure many years in an immersion, tidal or splash zone, or exposed to a salt-laden atmosphere (Melchers 2020). Saline inflows in coastal areas can also increase gravel and sand volume entering the facilities (sewers, PS or WWTP), contributing to the mechanical deterioration of the weakened materials.

Saline contributions can also substantially increase peak flow and volumes, using available system capacity and increasing the risk of discharges. Large volumes of saline inflows can come from direct connections when the elevation of a system's discharge or weir overflow are below the tidal level in a coastal area. Trends of sea-level rise because of climate change are expected to increase hydraulic pressure to these structures, resulting in increasing saline inflow volumes (Phillips *et al.* 2015). Reduction in capacity, both in the facilities and in the drainage system upstream, can contribute to increasing untreated wastewater overflows, in wet and dry weather, with subsequent environmental and public health risks. Exceeded capacity can be evaluated from the sewers' hydraulic point of view, as a relation between the income volumes and the cross-section capacity of the pipes, or from the increased risk to public health and property, given by the occurrence of overflows or flooding.

Salinity in wastewater can have a deleterious effect on the WWTP operation. Conventional wastewater treatment technologies as activated sludge (Osman *et al.* 2017) have been affected, as well as membrane bioreactors, because of a rapid loss in membrane permeability (Reid *et al.* 2006). The nitrification process can be inhibited (Osman *et al.* 2017). High percentages of salt have been recognized to compromise the operation of conventional aerobic wastewater treatment processes above chloride concentrations of 5–8 g/L (Lefebvre & Moletta 2006). Sludge settling in WWTP can be compromised for values above 3.5–5 g/L. Salinity can reduce or completely inhibit microbial activity in activated sludge. For salinity below 10 g/L, microorganisms could acclimatize in several weeks and achieve the same initial activity as in raw sludge. For salinity above 30 g/L, the acclimatization process was very slow or impossible (Linarić *et al.* 2013).

The reuse of wastewater for irrigation requires the control of salinity, as it can cause rapid soil salinization, affecting crops and hence degrading agricultural land (WHO 2006). Salinity is considered the most important parameter in determining the suitability of water for irrigation, as salts affect several processes in plant growth (Ayers & Westcot 1994). For such, treated water quality for reuse has long been established limits for chlorides (Osman *et al.* 2017). Salinity over 0.45 g/L has been recognized to restrict water use for irrigation, posing severe restrictions above 2 g/L (Ayers & Westcot 1994).

The inflow of saline waters can subsequently lead to higher operation and maintenance costs (Flood & Cahoon 2011). These can be because of effects in the treatment processes, repair, or replacement of concrete or metallic structures, gates, and other mechanical equipment, but also because of longer functioning hours of pumping or other equipment in the WWTP. Many small repairs undertaken by operational staff go unreported as saltwater-related damage (Phillips *et al.* 2015).

In Table 1, a summary of sources, mechanisms, effects, and consequences is presented.

Contextual factors and performance indicators

Contextual factors (Fi) and performance indicators (Pi) have been selected given the identified sources, causes or mechanisms, effects and consequences. Contextual factors are useful for locating the potential sources, causes or mechanisms and to complement performance indicators. Proposed performance indicators allow to quantify saline inflows' magnitude (P1) and to identify their causes (P2, P3, F1–F3) or consequences (P4–P10 and F4).

Contextual information to be collected and aggregated contextual factors are proposed in Table 2.

Performance indicators are proposed in Table 3, and a specific note is made for those coming from the literature review. The proposed reference values for each performance indicator derive from the bibliographic research made on each topic, which is synthesized after each equation.

The percentage of saline inflow magnitude (P1) can either be given by a quotient between the volume of saline inflow and the total inflow to a certain installation or, if these are not available, by the mass balance between the sum of the wastewater and saline water and the total inflow, as a quotient of salinities, as in (1).

$$P1 = \frac{V_{SI}}{V_T} = \frac{Sal_T - Sal_{WW}}{Sal_{SW} - Sal_{WW}} \ [\%] \quad (1)$$

where: V_{SI}: estimated yearly volume of saline inflow (m^3); V_T: yearly drained volume (m^3), Sal_T: total inflow salinity (g/L); Sal_{WW}: wastewater salinity (g/L); Sal_{SW}: saline water salinity (g/L).

Representative sampling should be ensured to determine this metric, as it closely relates to tidal cycles. As referred in the method, samples ought to be taken at least 8/day (every 3 h). It is recommended that P1 is given by the 95-percentile of the results.

As referred, wastewater salinity can vary with upstream conditions. Even if coastal water salinity may be rather constant for a location, local monitoring of total and wastewater salinities ought to be made. Alternatively, average values for wastewater salinity (Sal_{WW}) can be used, and local monitoring of total inflow salinity (Sal_T) ought to be made.

Given the references in the literature review, the Sal_T should be lower than 3.5–5.0 mg/L so as not to compromise the treatment processes in the WWTP (Tang & Lee 2002; Reid *et al.* 2006; Monte & Albuquerque 2010; Linarić *et al.* 2013; Osman *et al.* 2017). For standard values of Sal_{WW} of 0.4 g/L and Sal_{SW} of 35 g/L, these limits correspond to 9 and 13% for P1, given (1). If treated wastewater is to be used for irrigation, Sal_T should be limited to 0.45–1.92 g/L (Ayers & Westcot 1994; EPA 2004; WHO 2006), corresponding to 0.14–4.40% for P1, given (1). Limitations to Sal_T for exposure of concrete structures are less restrictive, provided the adequate concrete class, reinforcement coverage, and surface protection; this context factor was not considered in the determination of reference values for P1.

Table 1 | Overview of saline inflows sources, causes, effects and consequences in wastewater systems

Sources	Causes or mechanisms	Detrimental effects	Consequences
Direct saline inflows Groundwater infiltration Domestic effluents (from water supply) Industrial effluents Road salting	Direct inflow through sewers or discharge structures Infiltration through fissures, joints and other High salinity effluents from households, commercial facilities, or industries Runoff from roads where salt was used for deicing	Corrosion of materials (components and equipment) Increase of volumes entering the system, surcharge, flooding or untreated discharges Higher duration of pumping and treatment processes Lower treatment processes efficiency Lower treated wastewater quality Lower sewer sludge quality (if valuation in other uses envisaged) Restrictions in water reuse for irrigation	Higher operation and maintenance costs Lower useful life of assets, increased frequency of replacement Higher number of functional failures Non-conformity with discharge licenses Increased risk to public health and property Restrictions in the use of sludge and treated wastewater

Table 2 | Contextual factors (Fi) relevant for saline inflows assessment

Contextual information	Quantification or aggregation of contextual information
Mapping of areas with brackish water supply	F1 Exposure of critical manholes to saline waters [%]
Survey on saline diffuse water uses upstream	F2 Exposure of critical pipes to saline waters [%]
Mapping of coastal buffer where groundwater saline intrusion can occur	F3 Emergency discharges with exposure to saline waters without non-return valve [number]
Mapping of potentially saline industrial connections	F4 Exposure of facilities to saline waters [number]
Mapping of manholes directly in contact with surface coastal waters	
Mapping of facilities directly in contact with surface coastal or tidal saline waters	
Mapping of roads where salt for deicing is used	
Data on inspection of sewers and manholes for condition assessment (e.g., CCTV)	
Data on inspection of undue connections (e.g., tracers)	

Table 3 | Performance indicators (Pi) to support the assessment of saline inflows

	Performance indicator	Description
P1	Saline inflow in relation to total inflow [%]	Assess saline inflow magnitude. Percentage of total water volume collected corresponding to saline water
P2	Infiltration flow rate per manhole [(m^3/day)/manhole]	Assess whether manhole condition can be a source of groundwater inflow. Ratio of daily infiltration per manhole
P3	Infiltration flow rate per length [(m^3/day)/km][a]	Assess whether pipe condition can be a source of groundwater inflow. Ratio of daily infiltration per pipe length
P4	Gravel and sand removal [ton/km][a]	Assess whether specific sediments intrusion can be occurring. Ratio of gravel and sand inputs per pipe length
P5	Maximum hourly flow rate regarding full pipe flow [%][b]	Assess the used pipe capacity in dry-weather. Percentage of pipe capacity corresponding to maximum daily flow
P6	Overflows due to undue inflows per each 100 km of pipe length [number/100 km]	Assess pollution prevention, with regard to the control of untreated wastewater discharges into the receiving environment. Number of overflows because of undue inflows occurred in each 100 km of pipe length
P7	Flooding occurrences per 100 km of pipe length [number/100 km][a]	Assess the exposure of people and goods from floods. Number of flooding occurrences on public roads and on properties, originating from the sewer system, in each 100 km of pipe length
P8	Extension of pipes with degradation by saline water [%]	Assess the evidence of pipe material degradation because of saline inflows registered by visual inspection. Percentage of pipe length with sewers degraded by saline water.
P9	Costs associated with excessive inflows [%][c]	Assess the relative costs because of general undue inflows regarding quantity. Percentage of total costs because of excessive inflows
P10	Costs associated with saline water [%]	Assess the relative costs because of saline inflows. Percentage of total costs because of saline water, as given by P1

[a]based on Matos *et al.* 2003.
[b]based on Cardoso *et al.* 2006.
[c]based on Almeida *et al.* 2021.

Variables in P1 can also aid in the identification of causes for saline inflows. Monitoring Sal_{WW} and comparing results between drainage basins can support the identification of locations where water uses, or water supply upstream, might contribute to increased salinity in sanitary wastewater (e.g. using saline or brackish water for surface washing or flushing).

Exploring saline inflow causes, infiltration is evidenced in P2 and P3 (either through manholes or along the pipes) as in (2) and (3) (Matos *et al.* 2003). Exposure of critical sewer components to brackish or saline groundwater, when groundwater level because of tidal variation is above the sewers' invert, is given by F1 and F2, as in (4) and (5). The number of manholes and the sewer length is commonly available in the utilities' registry.

$$P2 = \frac{Inf}{M_{up}} \ [\mathrm{m^3/day \cdot manhole}] \tag{2}$$

$$P3 = \frac{Inf}{L_{up}} \ [\mathrm{m^3/day \cdot km}] \tag{3}$$

$$F1 = \frac{M_c}{M_T} \ [\%] \tag{4}$$

$$F2 = \frac{L_c}{L_T} \ [\%] \tag{5}$$

where: *Inf*: infiltration estimate, as the difference between the 25-percentile of the dry-weather flow in the wet and the dry season (m^3/day); M_{up}: manholes in the sewers upstream (number); L_{up}: length of sewers upstream (km); M_c: manholes in critical condition in the system exposed to saline waters (number); M_T: total number of manholes (number); L_c: length of pipes in critical condition in the system exposed to saline waters (km); L_T: total pipe length in the system (km).

Sewer components in critical condition might be those classified in classes 4 or 5 because of tightness anomalies, according to the standard EN 13508-2:2003+A1:2011. A parallel case study of 10 monitoring sites (Brito *et al.* 2021), 25- and 75-percentiles for P2 and P3 were studied, allowing the identification that 0.1–0.2 m^3/day.manhole can already compromise systems' performance.

Still, regarding causes, direct inflow from coastal waters might be perceived through F3, regarding the emergency discharges which invert level is exposed to tidal influence and that are not equipped with a non-return valve. Mapping this context factor, as well as M_c and L_c, provides a very useful insight into the location and dispersion of the saline inflow causes.

Exploring saline inflow consequences, in coastal areas, sand in the sewers might be caused by direct inflows. As in (6), P4 might signal this occurrence, but given its larger scope, regarding gravel and sand removal (as this metric comes from Matos *et al.* 2003, therein designated as *wEn14*), P4 should be investigated along with F3. If information regarding only sand removal is available, a narrower scope for P4 might be used.

$$P4 = \frac{W_{SS}}{L_{up}} \ [\mathrm{ton/km}] \tag{6}$$

where: *Wss*: Drained weight of grated solids and sands removed from PS and WWTP (ton); L_{up}: length of sewers upstream the WWTP (km).

For parallel case studies of four utilities (Almeida *et al.* 2018) and eight utilities (Brito *et al.* 2021), 25- and 75-percentiles for P4 were studied, which allowed the identification that 2.5–5.0 ton/km can already compromise WWTP performance. These results were discussed with participants from the utilities for an expert-based opinion.

Pipe surcharge is evaluated by P5, as in (7) (Cardoso *et al.* 2006). Data used for this metric should be restricted to dry-weather flow whenever stormwater contributions are expected. Naturally, a pipe surcharge can occur because of other reasons. Interpreting this metric's result should be accompanied by the evaluation of whether less satisfactory results occur simultaneously to higher tides.

$$P5 = \frac{DWF_{max}}{FPF} \times 100 \ [\%] \tag{7}$$

where: DWF_{max}: maximum dry-weather flow in the dry season (m^3/day); *FPF*: full pipe flow (m^3/day), given e.g. by the Gauckler-Manning-Strickler equation.

It is recommended that DWF_{max} is given by the 95-percentile of the results. In many countries, sanitary sewers are designed for approximately 50–75% full cross-section capacity (MOPTC 1995; CPHEEO 2013; Water UK 2019).

Increased risk to public health and property is denoted by P6 and P7, as in (8) and (9) (Matos *et al.* 2003). These indicators should assess pollution prevention, concerning the control of untreated wastewater discharges into the receiving environment and protecting people and goods from floods, understood as the flooding occurrences on public roads and properties originating from the sewer system.

Again, these occurrences might be because of other factors, so less satisfactory results should be read against, e.g., precipitation records.

$$P6 = \frac{O}{L_T} \times 100 \ [\text{n.}^\circ/100\text{km}] \tag{8}$$

$$P7 = \frac{F}{L_{SC}} \times 100 \ [\text{n.}^\circ/100\text{km}] \tag{9}$$

where: F: number of flooding occurrences of sanitary wastewater (number); L_{SC}: sanitary and combined systems pipe length (km).

Given their impact, a result of 0 for both metrics is desired. The Portuguese regulator (Alegre *et al.* 2017) refers that more than 0.5–2.0 flooding occurrences per 100 km have a noteworthy impact.

The chemical attack of construction materials can be evidenced by P8, as in (10), and signalled by F4, providing the number of facilities where concrete and equipment are recurrently exposed to saline waters.

$$P8 = \frac{L_{SI}}{L_T} \times 100 \, [\%] \tag{10}$$

where: L_{SI}: length of pipes with recurrent exposure to saline water and with surface degradation (km); L_T: total pipe length in the system (km).

The financial impact might be perceived by the results of P9 and P10, as in (11) (Almeida *et al.* 2021) and (12).

$$P9 = (V_T - V_{WW}) \times \frac{€/V_{av}}{€_T} \times 100 \, [\%] \tag{11}$$

$$\mathrm{P10} = \mathrm{V_{SI}} \times \frac{€/\mathrm{V_{av}}}{€_\mathrm{T}} \times 100 \tag{12}$$

where: V_T: total yearly drained volume (m^3); V_{WW}: estimated yearly volume of sanitary inflow, as the difference between the volumes corresponding to the 75- and the 25-percentile of the dry-weather flow in the dry season (m^3); $€/V_{av}$: average cost ($€/m^3$); $€_T$: total costs (€); V_{SI}: estimated yearly volume of saline inflow (m^3), which can be given by (1).

Reference values for Equations (10)–(12) were proposed and discussed with participants from eight utilities (Almeida *et al.* 2021).

In synthesis, reference values for the performance indicators P1–P10 are given in Table 4.

Identification of improvement options

As referred, undue inflows can be addressed and controlled through organizational, operational, and structural approaches. Organizational options can include internal reorganization of roles, responsibilities, and authorities; planning to address risks and opportunities; allocation of needed resources; improving staff competencies; enhancing stakeholder engagement and awareness; and improving documented information. Operational options concern maintenance activities; data acquisition; system diagnosis and analysis; and evaluation of procedures' implementation. Structural options can include rehabilitation, replacement, or construction activities.

The portfolio of options to handle saline inflows is identified in Table 5, coming from the literature review (Hyman 2005; Almeida & Cardoso 2010; ISO 2014; EPA 2015; Melchers 2020), the activities related to data collection required for the contextual information (in Table 2) and validation through expert opinion (Almeida *et al.* 2021).

Table 4 | Proposed reference values for the performance indicators

Ref	Performance indicator definition		Reference values Good; Acceptable; Unsatisfactory
P1	Saline inflow in relation to total inflow [%]	For WWTP efficiency	[0,9[; [9, 13[; [13, +∞[
		For reuse for irrigation	[0,0,14[; [0.14, 4.4[; [4.4, +∞[
P2	Infiltration flow rate per manhole [(m^3/day)/manhole]		[0, 0.1[;[0.1, 0.2[;[0.2, +∞[
P3	Infiltration flow rate per length [(m^3/day)/km]		[0, 5[;[5, 10[;[10, +∞[
P4	Gravel and sand removal [ton/km]		[0,2.5[;[2.5, 5.0[;[5.0, +∞[
P5	Maximum hourly flow rate regarding full pipe flow [%]		[0, 50[;[50, 75[;[75, +∞[
P6	Overflows due to undue inflows per 100 km of pipe length [number/100 km]		0;]0, 2[;[2, +∞[
P7	Flooding occurrences per each 100 km of pipe length [number/100 km]		[0, 0.5[;[0.5, 2.0[;[2.0, +∞[
P8	Extension of pipes with degradation by saline water [%]		[0, 1[;[1, 2[;[2, 100]
P9	Costs associated with excessive inflows [%]		[0, 5[;[5, 15[;[15, 100]
P10	Costs associated with saline water [%]		[0, 5[;[5, 15[;[15, 100]

Table 5 | Options to address and control saline inflows in drainage systems

Organizational	Operational
Tracking community funds applicable to the control of undue inflows	Mapping of areas with brackish water supply
Development of a specific plan to assess and control saline waters	Mapping of potentially saline industrial connections (e.g., agri-food, petroleum, or leather industries)
Training and capacity building with competencies for saline inflows management	Survey on saline diffuse water uses upstream (e.g., for washing, surface cleaning, road salting)
Staff (internal or external) allocation to the control of undue inflows	Inspection surveys for sewers' and manholes' condition assessment (e.g., CCTV)
Establishment of internal audits to verify to evaluate the implementation of procedures	Inspection surveys for undue connections detection (e.g., tracers) Monitoring water salinity in sewers, PS and WWTP
Articulation with other utilities dealing with urban water systems	Monitoring water salinity in the water supply system Monitoring groundwater salinity
Articulation with local stakeholders (e.g., costumers or water users)	Monitoring coastal water salinity
Implementing awareness-raising actions for the correct use of drainage networks	Monitoring precipitation and flow or water height in sewers Monitoring tidal height
Structural	Monitoring sand volumes in PS and WWTP
Rehabilitation of structural anomalies in pipes	Recording pumping cycles in the PS
Rehabilitation of structural anomalies in manholes	Monitoring groundwater table (e.g. With piezometers or recurring to local wells and water boreholes)
Correction of weirs' crest elevation	Testing concrete samples in sewers, PS, and WWTP
Protection of concrete and equipment from corrosion	Testing metal samples in equipment in PS and WWTP
Disconnection of direct connections between sewers and coastal waters	Modelling hydraulic behaviour of the sewer system
Installation of non-return valves in the direct connections between sewers and coastal waters	Asset registry update
Installation of solids retention chambers	Development, implementation and regular update of a GIS system
	Improvement of technical specifications for construction materials and equipment
	Integration of technical databases

Validation in a case study

The results of the application of the contextual factors and performance indicators to the case study are presented in Table 6. It should be noted that each contextual factor allows for a better understanding and zoning (when maps are available) of more exposed areas. Also, performance indicators should not be judged individually, as the indicators proposed complement each other, as each one provides a different point of view on the problem.

Results for the case study point out that saline volumes input is quite relevant (P1 of almost 30%), posing problems regarding corrosion, WWTP operation (as the utility reported), and relevant concrete exposure to intermittent saline waters, in PS and WWTP (F4).

Other related possible consequences can be the excessive sand inflow (P4) and augmented costs. Costs associated with saline water (P10) are almost 30%, in alignment with P1 (as, for this case study, the inflow volumes to the sector under analysis coincide with those that inflow the WWTP). Compared to other excessive inflows in the system (P9), saline inflows represent more than a third of the augmented costs.

There might also be a relation to overflows (P6) and flooding events (P7), but these would have to be further analyzed to exclude possible cumulative effects with stormwater inflows, as apparently there is no pipe surcharge downstream in dry weather (P5).

The major causes can be direct inflows from the collection system, as there seem to be no generalized infiltration problems (P2 and P3) and no emergency discharges without non-return valves, of the bulk system, with exposure to saline waters (F3). A small extension of exposed critical pipes and manholes has been identified (F1 and F2). However, as those are geographically concentrated in the downtown areas, it might mean that localized groundwater saline inflows can occur.

In addition, the utility recognizes a lack of knowledge regarding emergency discharges. The collection system is managed by other utilities, resulting in the absence of such information, relevant for the present diagnosis.

Given the presented results, a set of organizational, operational, and structural actions is envisaged. The most relevant options for the case study can be:

(i) articulate with local stakeholders, namely by enhancing information exchange with the utilities managing the coastal collection systems;
(ii) implement field surveys for undue connection detection, to find out every emergency discharge in the tidal-influenced area and plan for its protection with non-return valves;
(iii) execute CCTV or visual inspection of the critical pipes and manholes exposed to saline waters, for condition assessment, and plan the rehabilitation of those vulnerable to infiltration;

Table 6 | Results for the contextual factors and performance indicators in the case study

Ref	Performance indicator definition	Result
P1	Saline inflow in relation to total inflow [%]	29.4[a]
P2	Infiltration flow rate per manhole [(m^3/day)/manhole]	0.02
P3	Infiltration flow rate per length [(m^3/day)/km]	0.36
P4	Gravel and sand removal [ton/km]	21.3
P5	Maximum hourly flow rate regarding full pipe flow [%]	7.9
P6	Overflows due to undue inflows per 100 km of pipe length [number/100 km]	>2 (limited knowledge)
P7	Flooding occurrences per each 100 km of pipe length [number/100 km]	16.4
P8	Extension of pipes with degradation by saline water [%]	unavailable
P9	Costs associated with excessive inflows [%]	81.3
P10	Costs associated with saline water [%]	29.4
F1	Exposure of critical manholes to saline waters [%]	3.5
F2	Exposure of critical pipes to saline waters [%]	8.0
F3	Emergency discharges with exposure to saline waters without non-return valve [number]	0 (limited knowledge)
F4	Exposure of facilities to saline waters [number]	8 (out of 15)

[a]Reference values for WWTP efficiency were applied, as the utility is not reusing treated wastewater for irrigation.

(iv) analyze the reinforced concrete class (the exposure class should be compatible with tidal cyclical exposure to seawater) and equipment protection used in the facilities and plan for the protection of those vulnerable to corrosion.

The next step would be to prioritize the selected options and plan for their implementation. Priorities ought to be established based on the expected effects on system performance but also considering the resources (financial, technical, and staff), internal articulation (e.g., adjusting the scheduling to other interventions already planned by the utility or considering preparatory activities, such as information collection) and time for consolidating institutional relations with other organizations.

CONCLUSIONS

The paper presents a procedure for diagnosing undue saline inflows, namely its magnitude and, considering both the main causes and consequences, proposes contextual factors, performance indicators, and acceptance levels for the last. The aim is to identify the inflow's contribution to the system's performance, risk, and cost. From an IAM perspective, the method considers infrastructure specificities and interdependencies.

A portfolio of improvement options is given, which can be adopted depending on the assessment results, the information maturity of the organization, and its internal and external contexts.

The availability of a case study, for which previous knowledge and valuable data were accessible, allowed the application of most steps of the method. However, for those utilities with lower information maturity, determination of every context factor and performance indicator can be difficult to achieve. In such cases, an iterative procedure can be recommended: starting with the determination of the contextual factors (F1–F4); following with the determination of P1; concluding with the remaining metrics. This adaptation of the method can be scheduled with intermediate activities for information collection. A few activities identified (in Table 5), as operational options to address saline inflows, are closely related to the recommended contextual information (in Table 2).

Replicability opportunities are envisaged to apply the metrics to different functional areas (to prioritize the worst-ranked) or assess other drainage systems facing the effects of saline inflows.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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