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Assessment for which tide level saltwater intrusion occurs in a sewer network. Case study: Barreiro/Moita WWTP, Portugal

A. Figueiredo[a,*], L. Amaral[b] and J. Pacheco[c]

[a] Department of Environmental Sciences and Engineering, NOVA School of Science and Technology, NOVA University of Lisbon, Quinta da Torre, 2829–516, Monte de Caparica, Portugal

[b] CENSE, Center for Environmental and Sustainability Research, NOVA School of Science and Technology, NOVA University of Lisbon, Quinta da Torre, 2829–516, Monte de Caparica, Portugal

[c] SIMARSUL – Setúbal Peninsula's Sanitation, A.S., Barreiro/Moita WWTP, 2835–351, Lavradio Barreiro, Portugal

*Corresponding author. E-mail: agv.figueiredo@campus.fct.unl.pt

Abstract

Salt water from the Tagus Estuary has been identified in the influent at Barreiro/Moita Wastewater Treatment Plant (WWTP), Portugal. The saltwater intrusion occurs during high tide levels in the estuary throughout damaged sections and direct vectors in the sewer network, changing the wastewater characteristics impacting the WWTP processes. This work has designed a methodology to assess from which tide level in the Tagus Estuary saltwater intrusion occurs in the sewer network by measuring WWTP influent's electric conductivity (EC). The methodology identifies saltwater intrusion for tide levels higher than 3.10 m, increasing significantly for tide levels higher than 4.00 m. During this study, 86% of the days registered at least one high tide level higher than 3.10 m, and 8% higher than 4.00 m, demonstrating a considerable occurrence of saltwater intrusion in the system with a tendency to increase due to the mean sea level rise registered in the Tagus Estuary. To prevent it, it is necessary to map infrastructures and assess the most critical points.

Key words: electric conductivity, salinity, saltwater intrusion, sewer network, undue inflow, wastewater treatment plant (WWTP)

Highlights

- Assessment method to identify tide levels occurring through saltwater intrusion.
- Changes to wastewater characteristics in sewer networks which impact on WWTP processes.
- We assess and map infrastructure to highlight critical points in the sewer network.

INTRODUCTION

Salt water from the Tagus Estuary has been identified in the influent at Barreiro/Moita Wastewater Treatment Plant (WWTP), Portugal. The salt water enters the system during high tides in the estuary and it is been reported in other sewer networks (Serrano 2014; Phillips *et al.* 2015). Intrusion may occur throughout old and/or damaged sewer sections, joints, manholes, emergency overflow weirs' discharge points from combined sewer and storm water draining systems, or pumping stations' overflow weirs. Some of the emergency overflow weirs' discharge channels have retention valves that do not work properly; in other cases, they are non-existent, making them direct vectors for salt water into the sewerage. Saltwater intrusion is considered an undue inflow.

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Saltwater intrusion into sewer networks causes extensive structural damage, increasing maintenance costs (Phillips *et al.* 2015). One cause of structural damage to steel and concrete structures is sulphuric acid (H_2SO_4), generated by the oxidation of hydrogen sulphide (H_2S). The H_2S arises from sulphate (SO_4^{2-}) reduction by sulphate-reducing bacteria (Zhang *et al.* 2008). The increase in SO_4^{2-} load in the wastewater, due to saltwater intrusion, intensifies the problem.

It is generally recognized that corrective actions, to minimize the problem, should be taken upstream along the sewer network rather than downstream at the WWTP (Firer *et al.* 2008; Zhang *et al.* 2008; Talaiekhozani *et al.* 2016), being a helpful strategy to elaborate an accurate mapping of the sewer network and identify the most critical points of saltwater intrusion occurrence (Phillips *et al.* 2015; Talaiekhozani *et al.* 2016). The wide variety of high tide levels during tide cycles, and the degree of saltwater intrusion severity, make it difficult to reduce the impacts in the WWTP. The saltwater intrusion changes considerably the influent characteristics, affecting the process control (Metcalf & Eddy 2014); moreover, this undue inflow increases energy consumption in both sewer network and WWTP, pumping stations adding more operational costs to these systems.

Saltwater intrusion has a growing impact on WWTP management caused by the mean sea level rise, which increases the tide levels, intensifying the saltwater volume entering the sewer network. Climate changes can aggravate this problem. Analysis of the tide level time series dataset from the Cascais mareograph near the Tagus Estuary demonstrates a mean sea level rise of 2.20 mm·year^{-1} between 1999 and 2004, and 4.10 mm·year^{-1} between 2005 and 2016 (Antunes 2016).

The aim of this study is to contribute a strategy to assess tide levels for which saltwater intrusion occurs in sewer networks, assisting the assessment of the network's most critical points.

Characterization of Barreiro/Moita sewer network and WWTP

This work assessed the sewer network from the Barreiro/Moita WWTP, which collects urban and industrial wastewater and stormwater. Some network sections are old. There are substantial sewer network sections along Barreiro and Moita municipalities' coastal line with the Tagus Estuary. This facilitates saltwater intrusion into the sewer network, mostly in infrastructures below mean estuary water level. The water utility, SIMARSUL, S.A., manages the main sewer interceptors and pumping stations that receive wastewater from smaller networks managed by the surrounding municipalities and industries – Figure 1.

The Barreiro/Moita WWTP can treat up to 300,000 p.e. and comprises: initial pumping station, pretreatment, primary treatment with lamella plate settlers, followed by conventional aeration and then UV radiation disinfection. Primary sludge is gravity thickened, waste biological sludge is thickened by mechanical rotary drums. The thickened sludges are mixed and stabilised by anaerobic digestion, before dewatering by centrifuge and storage to final destination.

Saltwater impacts and counter measures practiced in the Barreiro/Moita WWTP

The saltwater intrusion changes considerably the influent characteristics, and in this case intensifies odour generation in the sewer network. Odours are attributed to H_2S in the sewer network generated by the action of anaerobic bacteria in the sewerage's biofilm. These anaerobic sulphate-reducing bacteria (e.g. *Desulfovibrio*) reduce the SO_4^{2-} present in wastewater into H_2S (McGhee 1991). The increase of H_2S concentration in the sewer network atmosphere is responsible for corrosion problems in the infrastructures, which are caused by acidification of the structural surfaces due H_2SO_4 generated biologically via H_2S's oxidation through biofilm's bacteria (e.g. *Thiobacillus*) present in the sewer top's section (McGhee 1991), and chemically by the condensed water vapor that absorbs atmospheric H_2S and oxygen (O_2), also generating H_2SO_4. Both oxidative processes occur with small presence of O_2 in sewer atmosphere. The corrosion caused by H_2SO_4 can reduce the concrete top

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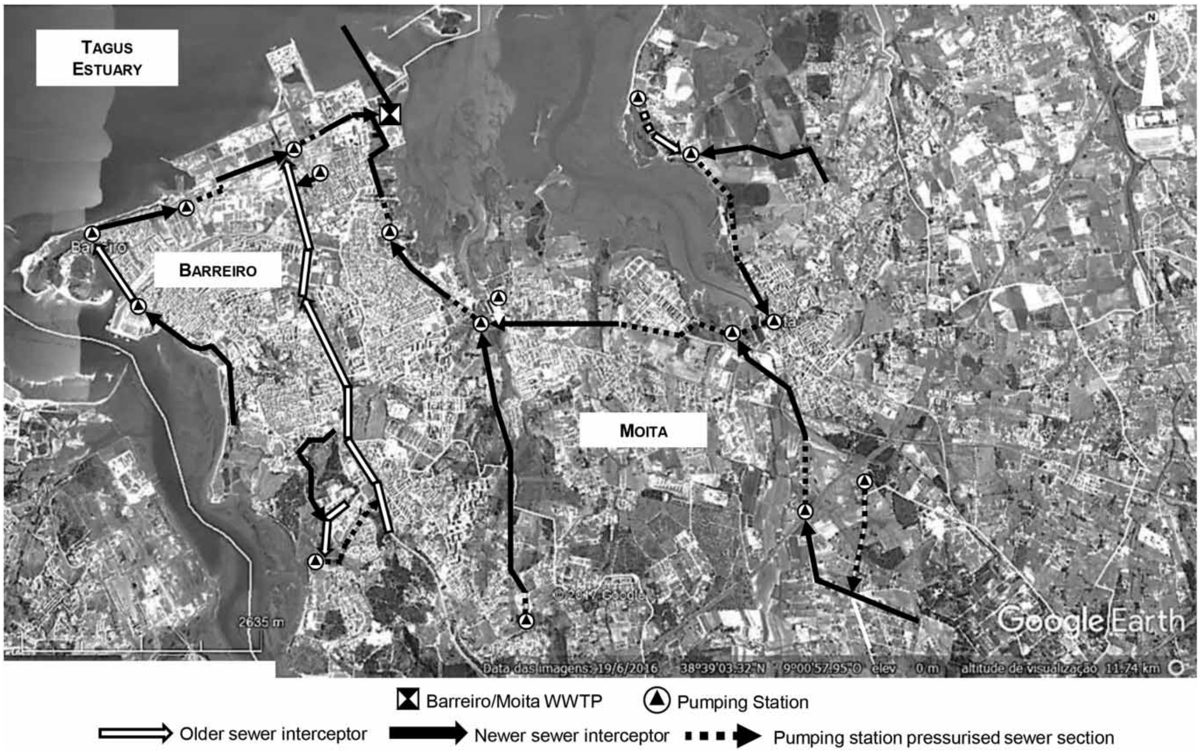

Figure 1 | SIMARSUL main interceptors and pumping stations' locations.

sewer section by 1–10 mm·year^{-1}, generating additional costs to water utilities (Zhang *et al.* 2008). Furthermore, higher concentrations of H_2S can cause harm to operation and maintenance workers' health (Firer *et al.* 2008).

The main changes in wastewater characteristics, caused by saltwater intrusion, are in its density, temperature, constituent loadings (e.g. chlorides (Cl^-) and SO_4^{2-}) and volume. Their impact in WWTP processes can, in extreme cases, affect the treatment compliance with regulations. The changes in density and temperature cause stratification in primary settlers, leading to a decrease of solids retention and process efficiency. Stratification leads to accumulation of denser and colder salt water in the bottom of the primary settlers, increasing the saltwater constituents (i.e. SO_4^{2-}) in primary sludges.

One of the most negative impacts arise in the sludge anaerobic stabilization process caused by high SO_4^{2-} loadings. The primary and biological thickened sludges represent each, on average, 50% (1:1) of the total digester feed sludge, and the main SO_4^{2-} contributor is the thickened primary sludge due to its higher electric conductivity values promoted by the stratification that occurs in primary settlers. The excess of SO_4^{2-} load through the thickened sludges leads to high H_2S content in the biogas produced, due to the activity of sulphate reducing bacteria in the anaerobic digester. The cogeneration system, which uses the biogas, stops when the maximum permitted H_2S value is exceeded, ceasing both electricity generation and heat recovery and lowering the anaerobic digester's temperature. These factors cause difficulties in keeping the anaerobic digestion process stable and efficient (e.g. decreases biogas yield). In the times series dataset of the Barreiro/Moita WWTP it is visible the correlation between the maximum tide level in high tide cycles and high H_2S content in the biogas produced. The variables show a similar sinusoidal behaviour and the peak values show a constant pattern of 5–7 days of delay between the maximum high tide level from the tide cycle and the peak of H_2S measured in the biogas circuit due to SO_4^{2-} load built up in the system.

The impact on WWTP processes has been attenuated by dosing ferric chloride ($FeCl_3$) in the plant's headworks. This has shown some benefits, including the reduction of the organic loading into the

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aeration basins and lowering of the biogas' H_2S concentration through ferrous sulphide (FeS) precipitation. The main problem is that tide level variation is highly dynamic, making difficult to take a proper corrective action. This work is a first approach to the problem that will permit determination of from which tide level in the estuary saltwater intrusion starts in the sewer network. In the future, forecasting models will enable the quantification of saltwater intrusion volumes and SO_4^{2-} loads, helping with $FeCl_3$ dosage.

METHODS AND MATERIALS

Tagus Estuary tide levels' times series dataset

Tide levels in the Tagus Estuary can be obtained from the forecasts on the Portuguese Hydrographical Institute (IH) website, which show the high and low tide levels and the day, hour and minute of occurrence, in this case for Lisbon Harbour. These data enable determination of the consecutive tide levels between the low and high tides (IH 2017) – see Figure 2. The mathematical equations provided by IH are presented below.

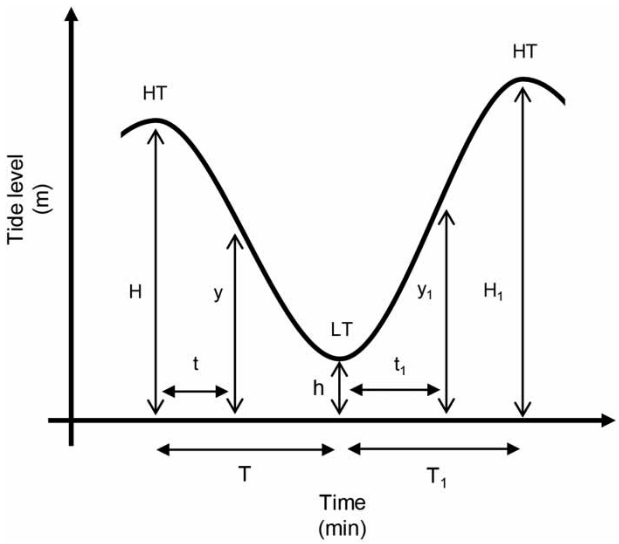

Figure 2 | Tide level variables (HT – high tide, LT – LT) (Adapted from IH 2017).

Equation (1) enables calculation of tide level, y (m), at any time between high tide and the next low tide:

$$y = \frac{H + h}{2} + \frac{H - h}{2} \times \cos\left(\frac{\Pi \times t}{T}\right) \tag{1}$$

Equation (2) enables calculation of tide level, y_1 (m), at any time between low tide and the next high tide:

$$y_1 = \frac{h + H_1}{2} + \frac{h - H_1}{2} \times \cos\left(\frac{\Pi \times t_1}{T_1}\right) \tag{2}$$

It is, thus, possible to generate a continuous time series dataset of tide levels covering the study period.

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Assessment of EC in the Tagus Estuary near the WWTP

The presence of salt water in WWTP influent can be observed by measuring its EC (APHA 1999; Serrano 2014). The EC of water depends on temperature and for a typical urban wastewater is between 680 and 2,038 μS·cm^{-1} at 20 °C (Metcalf & Eddy 2014). The EC of water from the Atlantic Ocean generally exceeds 40,000 μS·cm^{-1} at temperatures above 10 °C (Degrémont 1989).

The EC values in the Tagus Estuary near the sewer network were taken from time series datasets from floating water quality stations nearby in the Tagus Estuary (SNIRH/APA). The water quality stations' locations are shown in Figure 3 and the EC values summarised in Table 1. The minimum and maximum EC values were assessed for each station's time series dataset and the arithmetic mean calculated for the general minimum and maximum to obtain an expected EC range for the study area. The results comply with the tidal water movements expected in that part of the estuary,

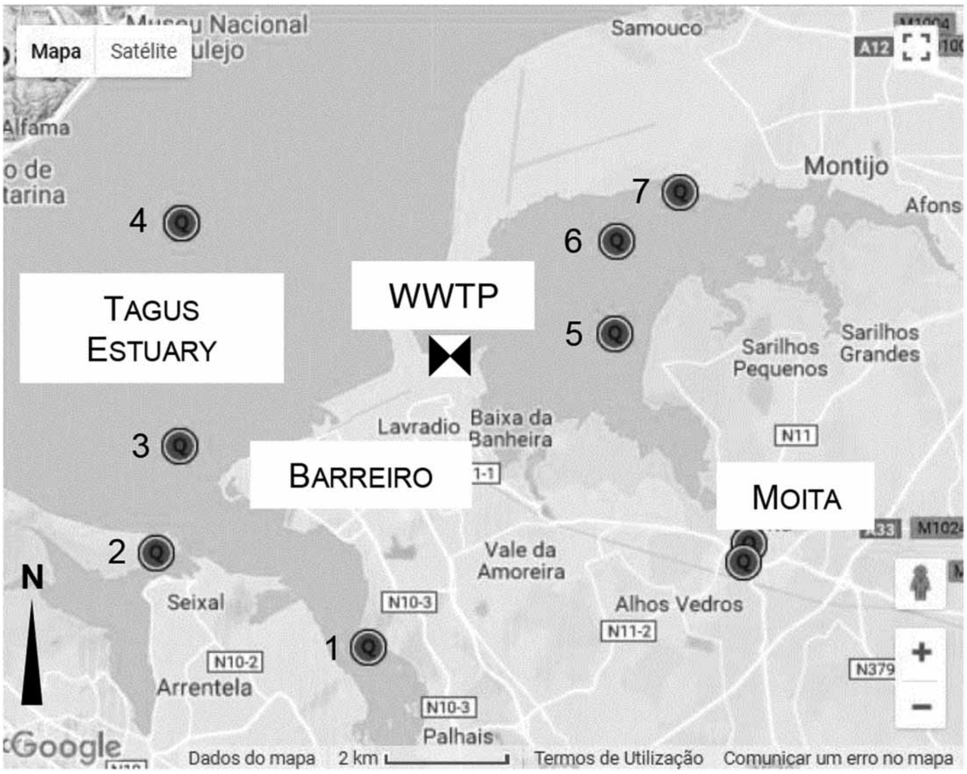

Figure 3 | Local floating water quality stations in the Tagus Estuary, Portugal (*Source:* SNIRH 2017).

Table 1 | Floating water quality station EC values for the Tagus Estuary (period of record 1999–2005)

Water quality station ID		EC (μS·cm^{-1})	
		Minimum	**Maximum**
1	ESTEIRO COINA (22C/05)	25,240	44,460
2	ESTEIRO SEIXAL (22C/06)	29,560	45,010
3	TEJO – BÓIA 14B – CANAL BARREIRO (22C/25S)	–	–
4	TEJO – WB1 – A (S) (21C/11S)	–	–
5	ESTEIRO MOITA (21C/06)	30,210	45,840
6	TEJO – ESTEIROS MOITA/MONTIJO (21C/10)	–	–
7	ESTEIRO MONTIJO (21C/07)	28,730	45,260
	General Arithmetic Mean	28,435	45,143

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for instance, high EC levels are expected at high tide due to incoming salt water from the Atlantic Ocean through the south side of the estuary and lower values at low tide, when ocean water returns and is replaced by less salty waters from the Tagus Estuary and other sources nearby.

Correlation between tide levels and WWTP influent's EC

The Barreiro/Moita WWTP has installed in its headworks influent channel an EC probe with a data logger to take EC measurements for each minute, enabling monitoring of the influent's EC variation through a time series dataset.

The saltwater intrusion impacts noticed in the WWTP process have different degrees of severity depending on tide cycle levels; for some lower tide cycle levels, the impacts can be unnoticed but for cycles with higher tide levels the negative impacts are highly significant. So, there is a need to assess from which tide level saltwater intrusion starts occurring in the sewer network. This assessment will help in identifying critical points on the sewer network for corrective actions.

The methodology uses two time series datasets: estuary tide levels and WWTP influent's EC. Both variables show similar sinusoidal behaviour when the tide levels generate significant saltwater intrusion. The sinusoidal behaviour is asynchronized in time due to the pumping station's delay effect and the hydraulic retention time of the sewer network. To correct this asynchrony, it is necessary to remove the pumping stations delay effect data and associate at the same minute both maximum values from high tide level and EC, generating a new and corrected EC time series dataset.

The next step is to create an assorted tide level dataset and remove its duplicates. This makes it possible to associate an arithmetic mean value of corrected EC time series dataset to each tide level. The resultant curve will reveal for which tide level saltwater intrusion in the sewerage starts occurring – see Figure 4.

Materials

The WWTP influent's EC was measured using a field probe (Endress + Hauser Indumax CLS50D) in the headworks channel, after the initial pumping station and before any chemical dosage ($FeCl_3$). The EC recorded was corrected to a standard temperature of 20 °C and data stored in a data logger for data analysis.

RESULTS AND DISCUSSION

Correlation between tide levels and WWTP influent's EC

The time series dataset used corresponds to a period between 1 April 2017 and 31 July 2017. In Figures 5 and 6, a specific portion of the EC time series dataset obtained for both distinct tide cycle periods is represented, with high and low tide levels, showing its difference when saltwater intrusion occurs. In Figure 5 the pumping station's ON/OFF effect on EC measurements is represented, and the hydraulic retention time in the sewer network can be approximately estimated by the time difference between the maximum high tide level in the estuary and the maximum influent EC value measured at the WWTP.

In both figures (Figures 5 and 6), a portion of the corrected EC time series dataset for low and high tide level cycles is shown, and in the first one the synchronized sinusoidal behaviour obtained after correction is well represented.

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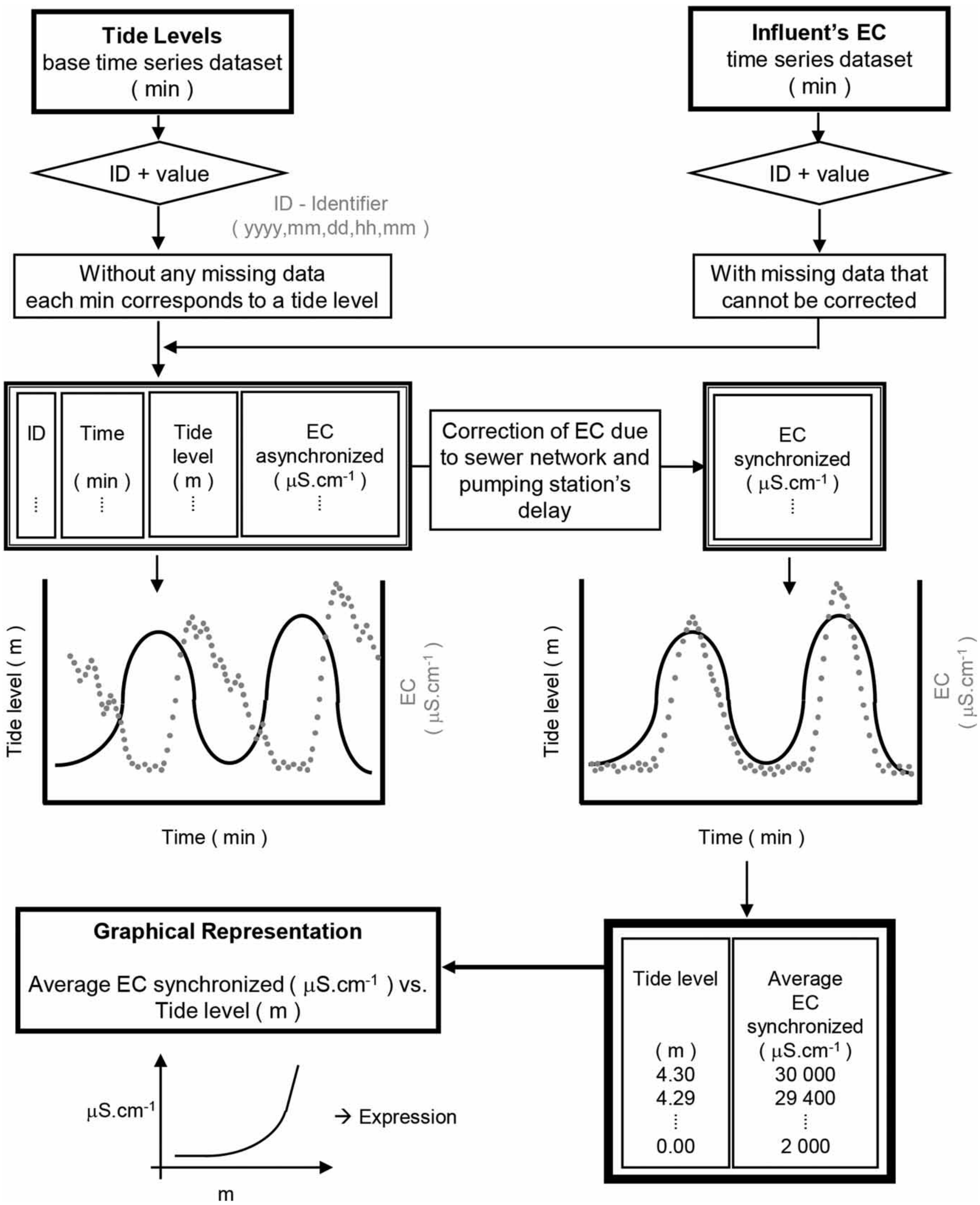

Figure 4 | Schematic to assess from which tide level saltwater intrusion in a sewer network starts to occur.

The tide level time series dataset was sorted, and duplicates removed, and for each tide level the corrected EC arithmetic mean values were obtained. The resultant dataset is graphically represented in Figure 7, and shows that saltwater intrusion occurs exponentially for tide levels higher than 3.10 m.

In a more in-depth observation for tide levels higher than 3.10 m, the curve has an intensifying effect to tide levels higher than 4.00 m, which is thought to be caused by direct vectors between

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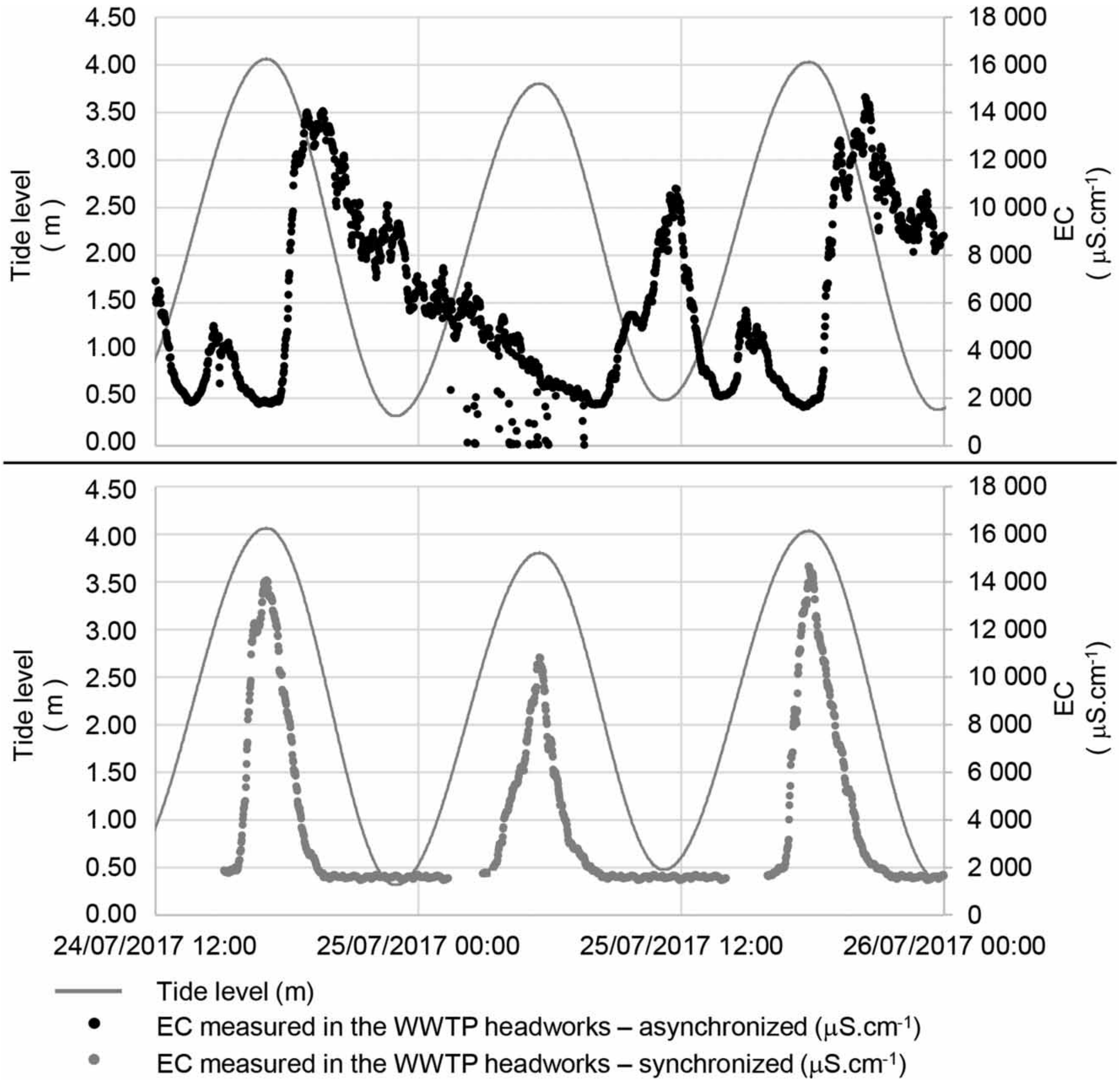

Figure 5 | Asynchronized and synchronized results for a high tide level cycle.

the estuary and the sewer network – see Figure 8. Both expressions show a strong correlation between the variables.

Thoroughly mapping the sewer network will enable identification of which possible direct vectors are critical contributors and which coastal areas are more affected by tide levels higher than 3.10 m. In these areas, high tide levels will make the underground saltwater level rise and increase the water pressure outside submerged damaged sewer network sections. In order to quantify saltwater intrusion occurrence, for the studied period, 86% of the days registered, there was at least one high tide level higher than 3.10 m and 8% had one high tide level higher than 4.00 m.

CONCLUSIONS

Saltwater intrusion into sewer networks is a significant problem. It is generally accepted that the best strategy is mapping and assessing the sewer network's critical points and taking corrective action as soon as possible. The climate changes will contribute to mean sea level rise, which will intensify the saltwater intrusion and increase operation and maintenance costs of these infrastructures to

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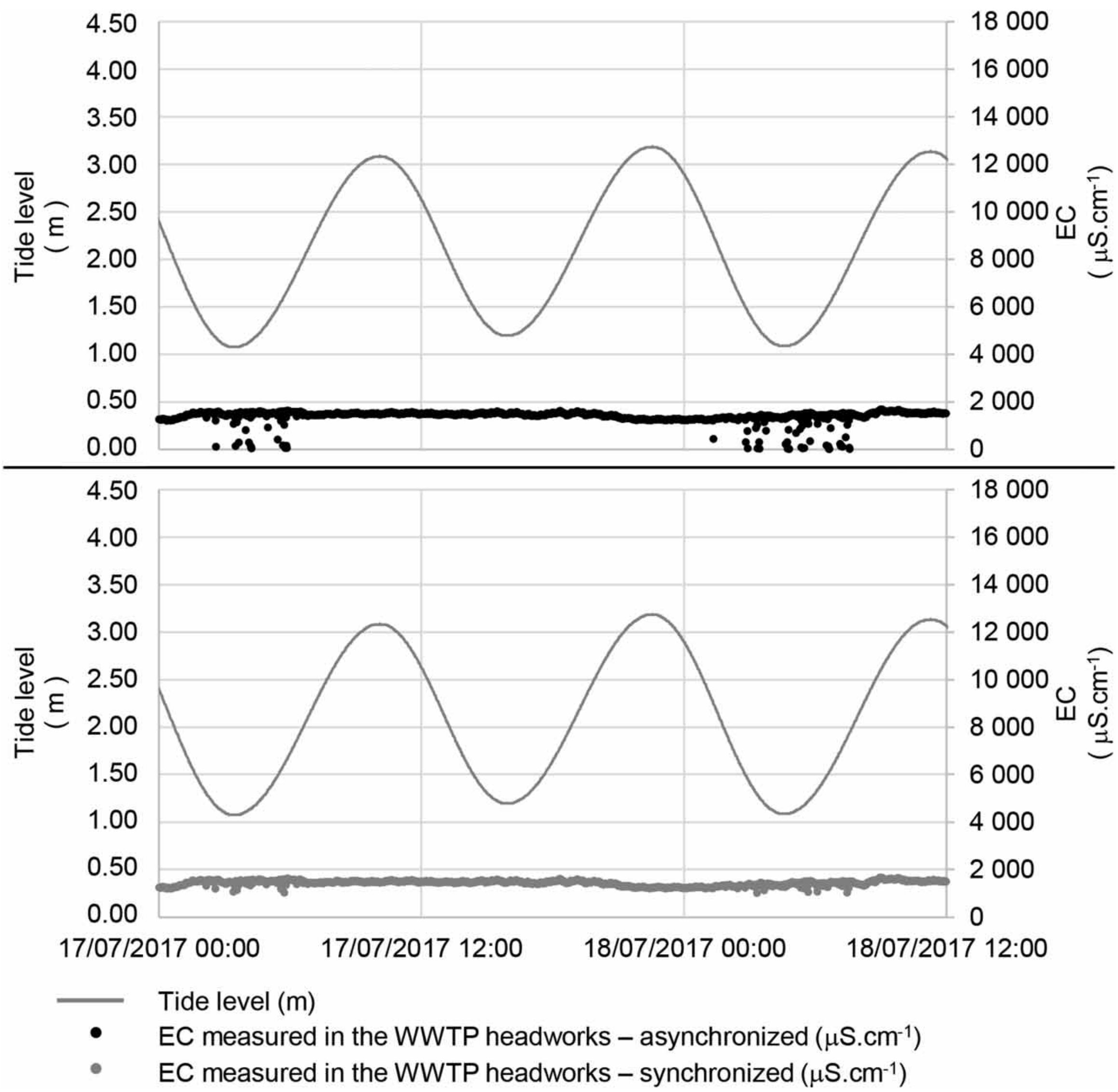

Figure 6 | Asynchronized and synchronized results for a low tide level cycle.

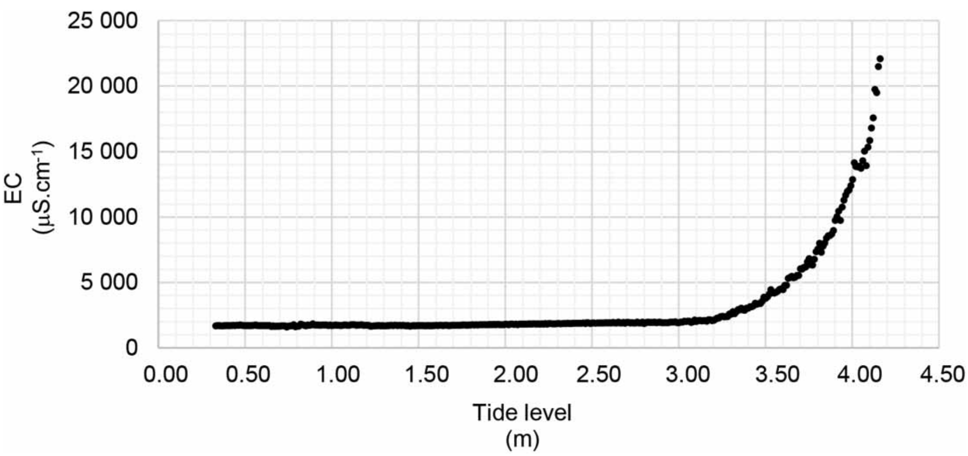

Figure 7 | Synchronized mean EC for each tide level.

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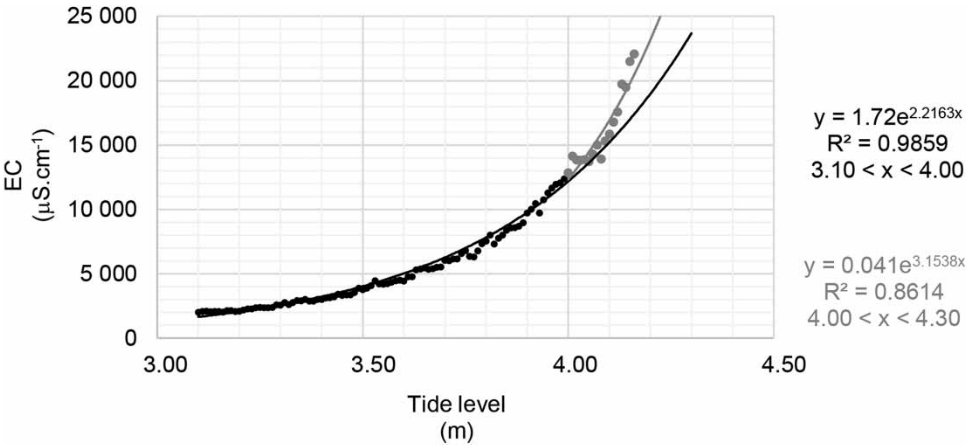

Figure 8 | Correlation between synchronized mean EC and tide levels.

water utilities. The saltwater intrusion also impacts considerably on the WWTP processes and can affect the treatment compliance with regulations.

This study showed the assessment of saltwater intrusion based on WWTP influent's EC measurements and its relationship with estuary tide levels to be feasible. With the tide levels provided by the IH for the Lisbon Harbour, in the Tagus Estuary, it was possible to assess that at the Barreiro/Moita WWTP's sewer network the saltwater intrusion starts to occur when tide levels are higher than 3.10 m, and for tide levels higher than 4.00 m the intrusion intensifies, exposing a possible existence of direct vectors between the sewer network infrastructures and the Tagus Estuary. Both variables, corrected influent's EC and estuary tide levels, have shown a strong correlation.

For the studied period, on 86% of the days registered there was at least one high tide level higher than 3.10 m, and 8% of high tides were higher than 4.00 m; these significant results might be incremented with the mean sea level rise tendency verified, not only in the Tagus Estuary but also in different coastal areas in the world.

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DATA AVAILABILITY STATEMENT

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

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