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Influence of climate change on wastewater treatment plants performances and energy costs in Apulia, south Italy

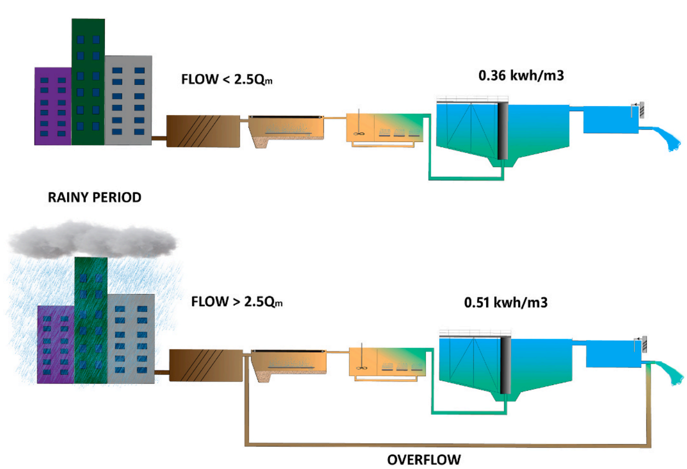
Ezio Ranieri [a,*], Gianfranco D'Onghia [a,f], Luigi Lopopolo [a], Petros Gikas [b], Francesca Ranieri [c], Eleni Gika [b], Vincenzo Spagnolo [d], Jose Alberto Herrera [e], Ada Cristina Ranieri [d,g]

[a] Universitá degli Studi di Bari, Dipartimento di Biologia, Bari, Italy
[b] Technical University of Crete, School of Chemical and Environmental Engineering, Chania, Greece
[c] Universitá degli Studi di Foggia, Dipartimento di Dipartimento di Economia, Management e Territorio, Foggia, Italy
[d] Politecnico di Bari, Dipartimento Interateneo di Fisica, Bari, Italy
[e] University Institute of Environmental Studies and Natural Resources (i-UNAT), Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain
[f] Consorzio Nazionale Interuniversitario per le Scienze del Mare CoNISMa, Italy
[g] Universitá Internazionale Telematica Uninettuno, Roma, Italy

HIGHLIGHTS

- As Rain intensity rises, wastewater influx into WWTPs increases.
- Rainfall intensity influences negatively electrical consumptions.
- BOD removal is lower with increasing annual precipitations.
- Temperature influences BOD, COD and SST removal efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper studies the influence of temperature and of rainfall intensity and the effect of such variations on the treatment efficiencies and on the electrical consumptions in seven medium-large size Wastewater Treatment Plants (WWTPs) in Apulia in South Italy (Bari, Barletta, Brindisi, Lecce, Foggia, Andria and Taranto).

It has been observed, in the considered WWTPs, a slight but clear increase of the incoming flow due to the increase in rainfall intensity, which results to an increase of the energy consumption per incoming volume.

The impact of the climate change to the incoming flow, during the last five years (2016–2020), has been assessed indicating that an increase in rainfall intensity results to an increase of the WWTPs energy consumptions

* Corresponding author.
E-mail address: ezio.ranieri@uniba.it (E. Ranieri).

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per wastewater treated volume. More specifically, for a specific WWTP (Lecce) it was found that the electrical consumption increases from 0.36 kw/m^3 to 0.51 kw/m^3 when the rainfall intensity was increased from 0.8 mm/min to 2.9 mm/min.

Some adaption measures have been considered to upgrade the existing WWTP so to mitigate the energy increase and to limit the global effects of climate change.

1. Introduction

Wastewater treatment plants (WWTPs) represent prominent energy consumers within municipal infrastructure, constituting approximately 3% of global electricity consumption (McCarty et al., 2011; Ciudin et al., 2014; Li et al., 2015; Ranieri et al., 2017; Lu et al., 2018). Concurrently, WWTPs are recognized as significant contributors to Greenhouse Gas (GHG) emissions, specifically through the direct release of CO_2, N_2O, and CH_4 resulting from biological processes involved in carbon, nitrogen, and phosphate removal, biosolids management, and off-gas emissions from wastewater collection systems. Additionally, indirect emissions arise from CO_2 generated during energy consumption (Yapıcıoğlu et al., 2021; Ranieri et al., 2023).

Acquedotto Pugliese (AQP), overseeing 184 WWTPs in Southern Italy (Apulia), is committed to reducing CO_2 emissions by optimizing biological and mechanical processes to conserve energy and mitigate emissions of CH_4 and N_2O. Given the correlation between CO_2 production and energy consumption in wastewater treatment, reducing energy requirements not only decreases CO_2 emissions but also aligns with cost-effective treatment practices (Ranieri et al., 2017; Van Lienden et al., 2010; Petrella et al., 2016a; Petrella et al., 2016b; Al Bataina et al., 2016; Herrera-Melián et al., 2020). Recent studies propose leveraging wastewater and biosolids for diverse applications to achieve energy cost reductions and GHG emission minimization (Ranieri and Świetlik, 2010; Capodaglio et al., 2016; Gikas, 2017; Menduni et al., 2020; Ranieri et al., 2021).

However, climate change significantly impacts WWTP operations, manifested by elevated wastewater temperatures and increased inflow rates. While Nordic climates exhibit limited influence on wastewater effluent quality from weather factors, temperate climates like Apulia experience substantial effects, impacting effluent quality through variations in air temperature, precipitation, and snowmelt (Ranieri, 2012; Gorgoglione et al., 2016; Kalimeris et al., 2017; Kinnunen et al., 2023). Elevated average temperatures affect oxygen solubility, microbial metabolism, and biodegradation processes, potentially compromising Biological Oxygen Demand (BOD) levels and causing detrimental effects on aquatic ecosystems and communities (Ranieri E. 2003; James Hughes et al., 2021).

The uncertainty associated with future climate exacerbates the challenges. Climate change impacts can yield conflicting effects on wastewater treatment costs, where prolonged droughts and warm conditions promote treated wastewater as an alternative to natural freshwater, while extreme climate events may escalate treatment expenses and reduce effectiveness (Reznik et al., 2020). Adverse impacts such as warmer temperatures, increased precipitation, and rising sea levels further compound the challenges faced by WWTPs (Zouboulis and Tolkou, 2015; Bassin et al., 2021).

The identified impacts on the wastewater network can be categorized into three main themes: (i) nuisance flooding, spills, and odors, (ii) deterioration of water quality due to increased uncontrolled discharges, and (iii) damage to infrastructure (James Hughes et al., 2021). Heavy rains during extreme weather events elevate energy demands for pumps, posing risks to facilities near sea level. Conversely, intense drought periods result in olfactory issues, cavitation of pumps, and potential damage to pipe systems. Furthermore, rising temperatures may decrease oxygen solubility, affecting microbial consortium and compromising the efficiency of biodegradation processes, potentially reducing removal efficiencies in key parameters such as BOD, COD, N, and P (Mailhot and Duchesne, 2010). Notably, monthly inflow rates exhibit a linear relationship with monthly rainfall, demonstrating moderate to strong correlations with wastewater treatment indicators (Li et al., 2018).

In Apulia, the climate change induced increase in intense rainfall that significantly impacts on WWTP performance and operational costs. A comprehensive analysis has been carried out on the seven largest WWTPs in Apulia (Foggia, Andria, Bari, Brindisi, Lecce, Taranto, and Barletta) serving over one million Person Equivalent (PE).

The primary objective is to evaluate the influence of temperature and wastewater flow variations on WWTP efficiencies and electrical consumption. Additionally, new technical measures are proposed to address these challenges, aiming to conserve energy and limit GHG emissions.

2. Materials and methods

In this investigation, a comprehensive five-year dataset covering from 2016 to 2020 was examined, including operational data sourced from wastewater treatment facilities situated in the Apulian region, Italy. Additionally, extensive climatic data covering the preceding 60 years were systematically acquired from major Apulian cities, namely Foggia, Andria, Bari, Brindisi, Lecce-Squinzano, and Taranto, with a focus on critical parameters such as temperature and precipitation.

The preparatory phase of the data analysis involved in accurate procedures, including data cleaning and setting.

Statistical analyses, specifically regression and time series methodologies, were employed to elucidate the complex correlations existing between wastewater treatment performance and various climatic variables. The parameters subjected to assessment included the following climatic and wastewater treatment plant (WWTP) variables.

- Rainfall intensity (measured in mm/min): Calculated as the ratio of the maximum annual rainfall over the minimum 5-min interval.
- Average temperatures.
- Extreme temperatures: Including both minimum and maximum values.
- Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS).
- Daily flow rate (measured in m^3/d).
- Energy consumption (kwh/d).

The validity of WWTP inflow data linear regressions was individually assessed through R-squared values. It has been performed the Kruskal-Wallis test, revealing a p-value <0.05. Correlation tests were also conducted, confirming the trends observed in the regressions. About the daily rainfalls it has been considered the 95th percentile value, on annual basis, that corresponds at 20 mm/d (Breugem et al., 2020) (see Fig. 1).

3. Results and discussion

In the present investigation, noticeable trends in temperature and rainfall intensity were examined across seven wastewater treatment plants (WWTPs) in the Apulian region. Fig. 2a illustrates the mm/min intensity of rainfall recorded over the past 60 years in the following WWTPs: Foggia, Andria, Bari, Brindisi, Lecce-Squinzano, and Taranto. In Fig. 2a, a significant increasing trend in rainfall intensity was observed for all investigated WWTPs. In 1962, rainfall intensity ranged from 1.00 (Barletta) to 1.40 (Lecce) mm/min, while in 2020, it varied between 1.62 (Bari) and 1.85 (Andria) mm/min. The calculated increases in rainfall intensity for each WWTP are as follows: 0.65 mm/min (Barletta), 0.70 mm/min (Foggia), 0.72 mm/min (Andria), 0.62 mm/min (Brindisi), 0.62 mm/min (Taranto), 0.34 mm/min (Bari), and 0.4 mm/min (Lecce).

Subsequently, Fig. 2b illustrates a discernible increase in average air temperature across the seven WWTPs, rising from 16.2 °C to 17.9 °C over the same period.

Fig. 2c shows the trend of annual extreme and average temperatures, demonstrating a noteworthy rise in average minimum extreme temperature, while the average maximum extreme temperature experienced a slight increase across all investigated WWTPs.

The influence of temperature on the removal of wastewater contaminants was then evaluated. Fig. 3a and b illustrate the correlation between Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS) removal percentages and concentrations, respectively, with temperature. Both figures highlight a reduction in pollutant removal efficiency with increasing temperature. This phenomenon can be attributed to decreased oxygen solubility affecting microbial metabolism and biodegradation processes, compromising established BOD levels and potentially impacting aquatic ecosystems (James Hughes et al., 2021).

Furthermore, the correlation between rainfall and incoming wastewater volumes (m^3/d) was investigated, particularly in the case study of Squinzano (Lecce) WWTP. A linear relationship was identified between monthly inflow rate and rainfall, with both demonstrating moderate to strong correlations with crucial wastewater indicators. Analysis of the Lecce-Squinzano WWTP highlighted a greater difference between inflow and outflow rates during rainy days, as depicted in Fig. 4. This behavior is emphasized in Fig. 4, reporting three year and more than 1000 flow data observed which illustrates a positive correlation between inlet flowrate and rainfall intensity.

This behavior is better illustrated in Fig. 5, which shows a strong positive correlation between the inlet flowrate to the Lecce-Squinzano WWTP with rainfall intensity, The linear interpolation curves follow equations y = 216,66x + 4834,5. In fact, the line starts at a base flow rate of approximately 5000 m^3/d and reaches nearly 16,000 m^3/d on days with rainfall of about 50 mm/day. In wastewater treatment plants, the phenomenon of increased flow rate during heavy precipitation is often evident. As rain intensity rises, the runoff from paved surfaces increases, leading to a substantial influx of water into sewage treatment systems. The increased flow can impact treatment efficiency, potentially affecting the removal of contaminants.

A decrease in BOD removal efficiency with increasing annual precipitations was observed, probably due to washing effect in the biological section, this behavior is shown also as function of annual rainfall as illustrated in Fig. 6.

Subsequently, the energy consumption of the seven WWTPs in relation to air temperature and rainfall intensity was evaluated. Fig. 7a and b showcase the impact of climate change on energy consumption over the last five years (2016–2020). A positive correlation was noted between energy consumption and the number of rainy days with more than 20 mm/d, representing the 95th value (Fig. 7a), as well as with rainfall intensity (Fig. 7b).

Examining the data from Apulian WWTP, it was concluded that rainfall intensity influences electrical consumption and management costs, with electrical consumption increasing from 0.36 kwh/m^3 to 0.51 kwh/m^3 as rainfall intensity rises from 0.8 mm/min to 2.9 mm/min.

The energy utilization in a wastewater treatment plant (WWTP) is related with flow, serving as a critical component for the acquisition, treatment, and distribution of water (Demir and Yapıcıoğlu, 2019; Yapıcıoğlu and Yeşilnacar, 2020; Yapıcıoğlu and Yeşilnacar, 2022). This energy consumption is strictly associated with indirect emissions, which, constitute the primary contributors to the overall greenhouse gas (GHG) output (Demir, Ö., & Yapıcıoğlu. 2019; Goliopoulos et al. 2022). The indirect emission can be calculated multiplying the emission factor

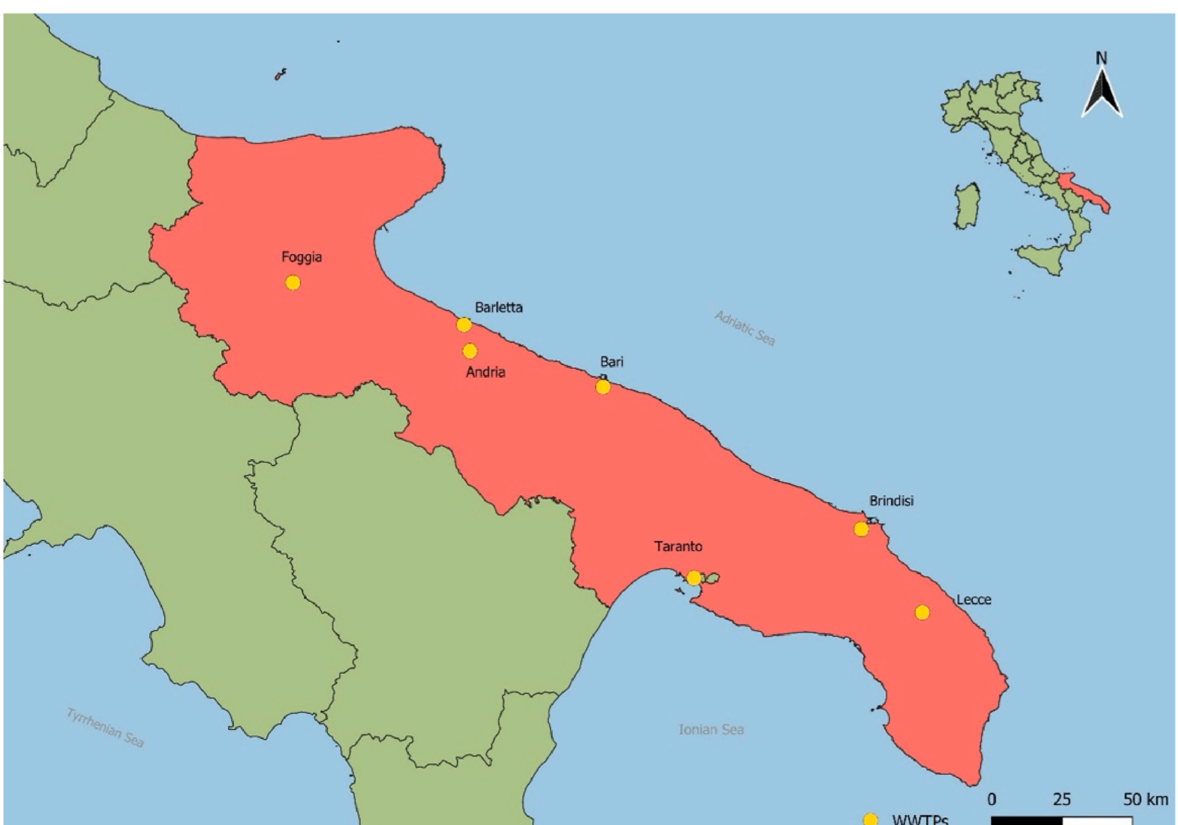

Fig. 1. Apulian WWTPs location.

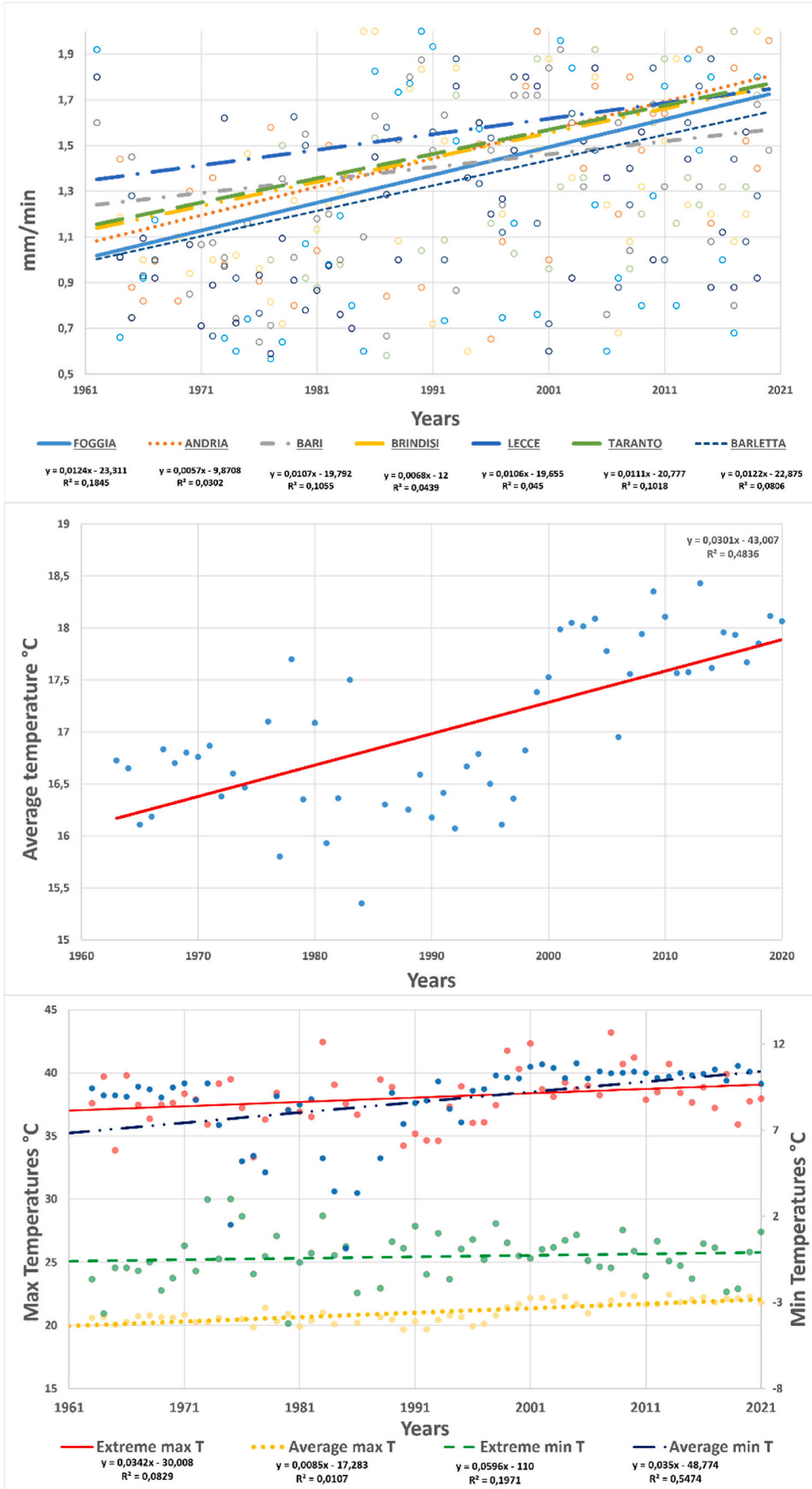

Fig. 2. Trends in the seven Apulian WWTPs locations under study during the last 60 years. (a) Rainfall intensity. (b). Average temperature. (c) Maximum and minimum temperature.

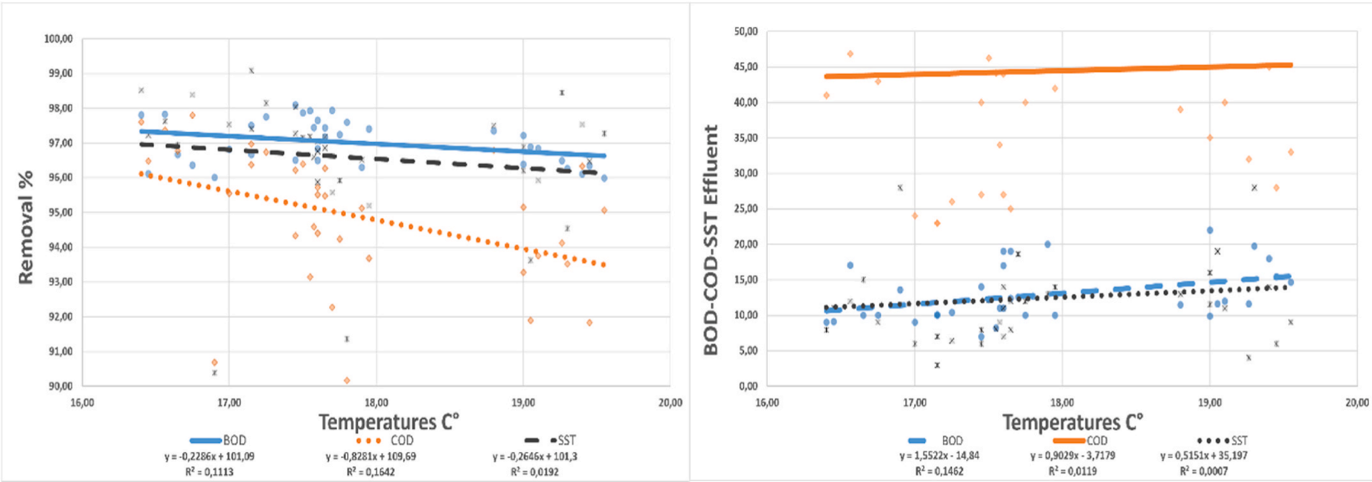

Fig. 3a. Trends of BOD, COD and TSS removal versus temperature, Fig. 3b Trends of the BOD, COD and TSS content in the effluent versus temperature.

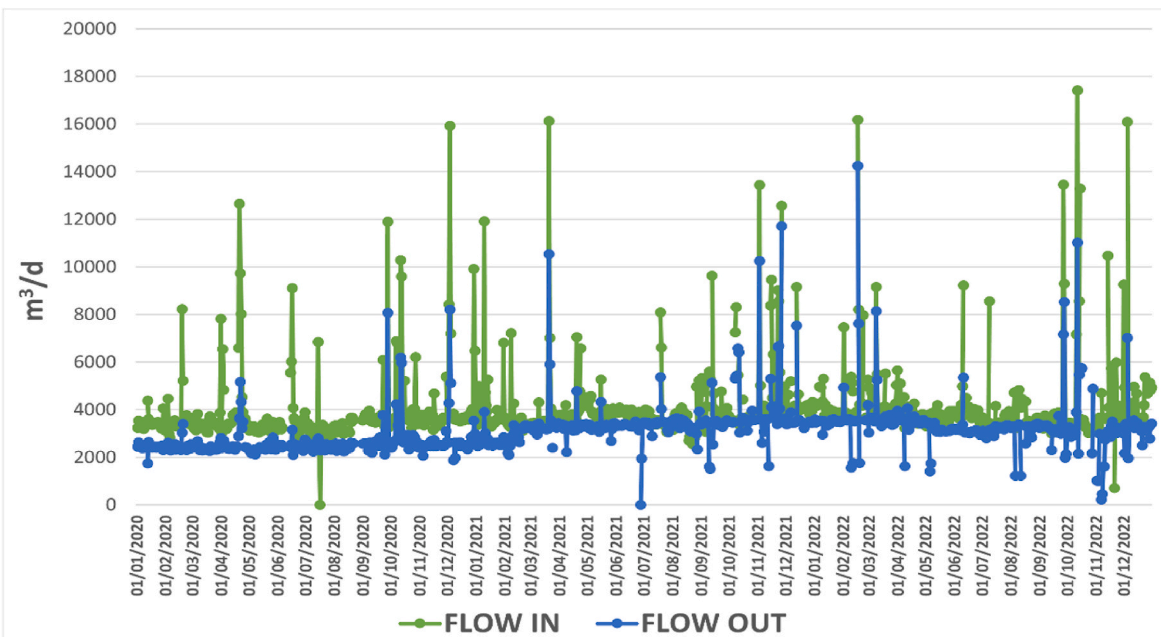

Fig. 4. Incoming and exiting flows at Lecce-Squinzano WWTP.

of electric energy for electric consumption. The emission factor reported by Acquedotto Pugliese (Acquedotto Pugliese AQP, 2019-21) is 0.406 $kgCO_{2eq}/kwh$; so a contribute ranging from 0.13 to 0.20 $kgCO_{2eq}/m^3$ should be associated to electrical energy.

The positive correlation between rainfall intensity and energy consumption focusses the impact of climate change on WWTPs operations.

The results highlight the need for adaptation measures to mitigate the adverse impacts of climate change on wastewater treatment. These measures involve the installation and operation of new pumping stations, upgrades to existing infrastructure, installation of protective structures, and the adoption of new distribution pipelines (NACWA, 2009). Optimization of pump working ranges and algorithms, coupled with the use of inverters, can yield energy savings ranging from 5 to 30% (Cardoso et al., 2021; Panepinto et al., 2016). Additionally, increased precipitation necessitates the implementation of green infrastructure measures to reduce runoff volume, alongside the adoption of rapid-response treatment technologies (Vo et al., 2014).

A significant portion of the sewage systems in high-income countries was built 30–50 years ago or even earlier (Baum et al., 2013; Willems, 2013). These systems are now nearing the end of their operational lifespan (O'Neill, 2010) and are inadequately equipped to contend with the emerging intensified rainfall patterns associated with climate change (Mailhot and Duchesne, 2010). Consequently, strategic interventions such as reinstallation, repair, or replacement are imperative to adapt to the evolving challenges posed by climate change.

Furthermore, leveraging effluent wastewater for reuse purposes in agriculture or industry, with the use of accumulation tanks positioned at lower elevations than wastewater treatment plants (WWTPs), holds promise in mitigating sudden flow increases by facilitating the storage of treated wastewater.

Finally, an accurate and targeted study aimed at reducing greenhouse gas (GHG) emissions from WWTPs should be undertaken and brought to completion. Such a study is essential for identifying and implementing effective strategies to minimize the environmental impact of wastewater treatment processes and align them with sustainability goals.

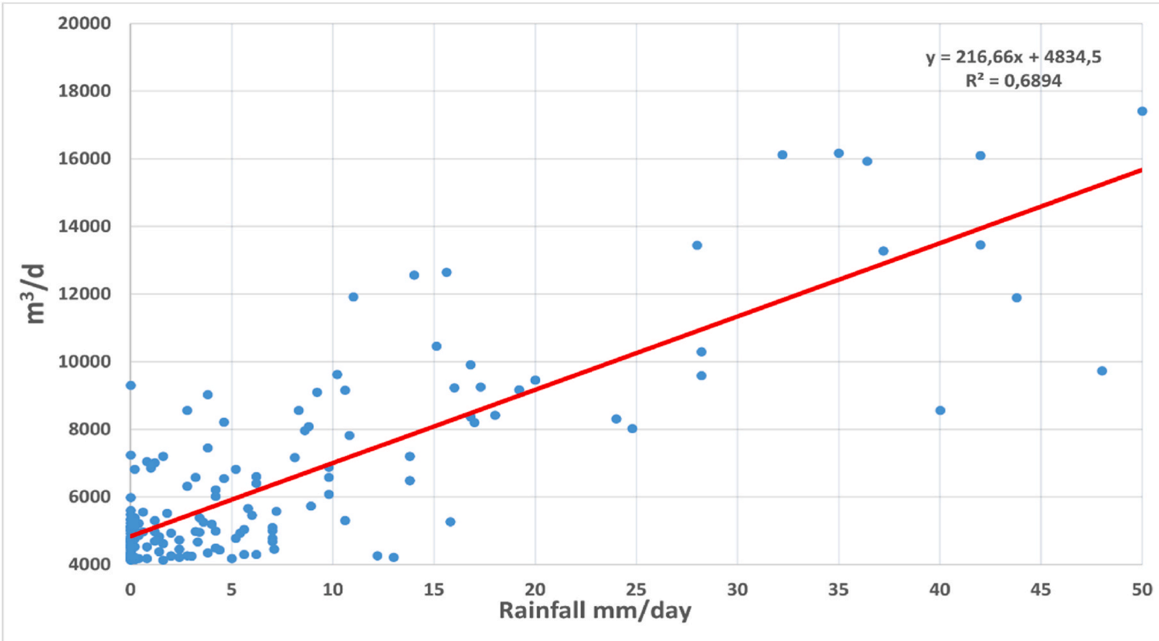

Fig. 5. Correlation between inlet hourly flowrate (m^3/d) and rainfall intensity (mm/day) at Lecce-Squinzano WWTP.

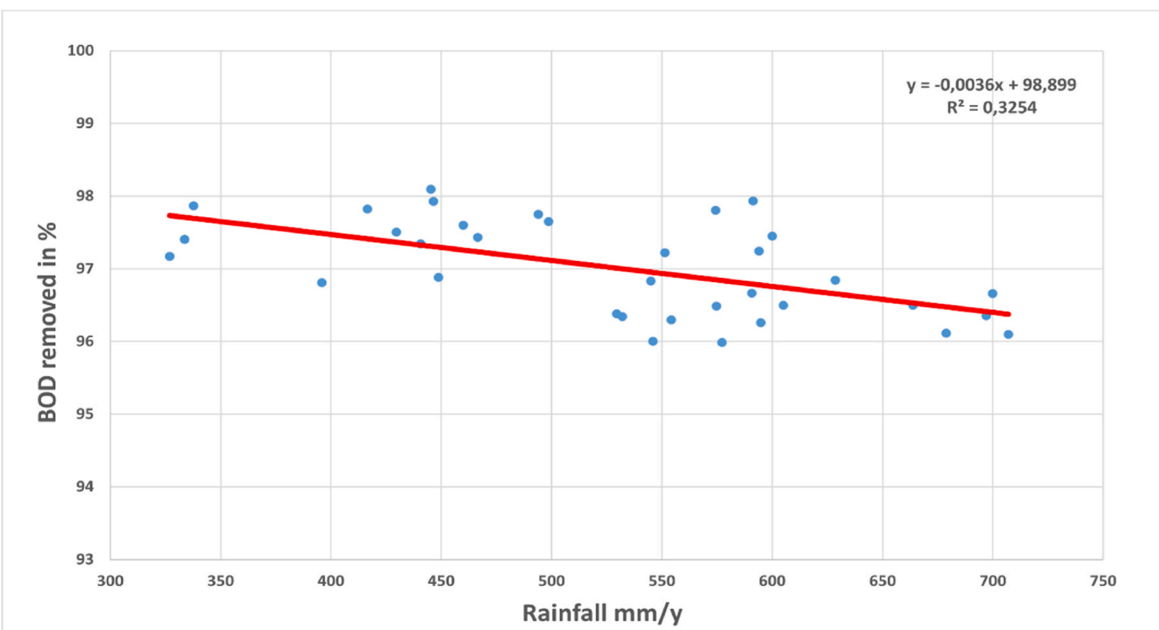

Fig. 6. Trend of the BOD removal as function of the annual precipitation.

4. Conclusions

The impact of climate change on municipal wastewater operation and maintenance has been showed to be significant, therefore a new conceptual framework governing the design and operation of WWTPs, and sewerage networks should be applied. The intensity of rainfall has been examined, revealing a general reduction in the removal efficiency of key wastewater contaminants. Furthermore, a direct positive correlation between rainfall intensity and incoming wastewater flow at the WWTP has been established and empirically validated.

Interpolation curves has been developed to assess the energy consumption (kwh/m^3) related to rainfall intensity and frequency, showing the direct correlation between climate change and energy consumption as matter of fact the raising from 0.36 to 0.51 kWh/m^3 due to raising rainfall intensity from 0.8 to 2.9 mm/min. Considerations include the need for installing new and improved pumping stations. Additionally, the strategic selection of new sites at lower altitudes, where applicable, for the discharge of WWTP effluent flows, potentially facilitated by gravity, emerges as a crucial adaptation strategy.

CRediT authorship contribution statement

Ezio Ranieri: Visualization, Validation, Supervision, Methodology, Conceptualization. **Gianfranco D'Onghia:** Writing – review & editing. **Luigi Lopopolo:** Resources. **Petros Gikas:** Formal analysis. **Francesca Ranieri:** Writing – original draft, Conceptualization. **Eleni Gika:** Data

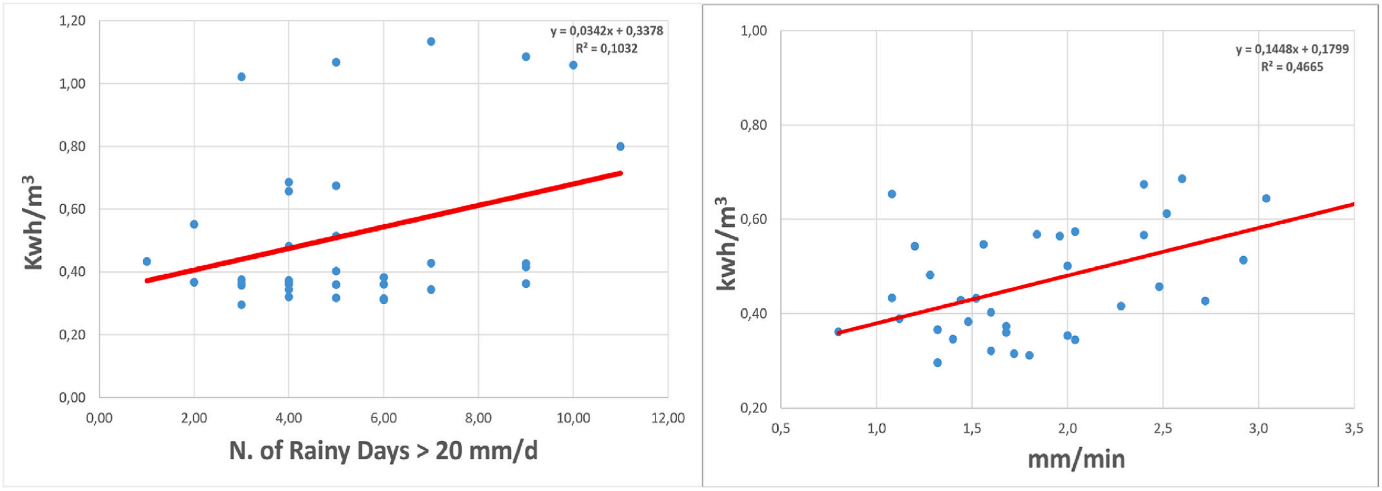

Fig. 7a. Trend of energy cost in term of kwh/m^3 as function of the number of the rainy days with more 20 mm/d; Fig. 7b. Trend of energy cost in term of kwh/m^3 as function of the intensity of precipitations in mm/min.

curation. **Vincenzo Spagnolo:** Investigation. **Jose Alberto Herrera:** Supervision. **Ada Cristina Ranieri:** Validation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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