An integrated modelling framework to assess cascade water reuse in urban areas

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INTRODUCTION

Water scarcity is an increasing problem for many countries worldwide, and the need for sustainable management of water resources is an urgent concern to face rising environmental challenges (Fernandes and Cunha Marques, 2023). This has prompted a rethink of water resources management and the reuse of water has gain growing interest. There is currently a strong focus on increasing reclaimed wastewater reuse, especially for agriculture (Delli Compagni et al., 2020). Besides, the ever-increasing costs associated with conventional energy sources have impelled the energy sector to transition towards more distributed and efficient energy production for heating/cooling purposes by exploiting local sources, especially across urban areas (Valancius et al., 2019). Typical applications are heat pumps using local groundwater reservoirs, and subsequently discharging the withdrawn water into the nearby surface water recipients, being natural or artificial water channels. Moreover, to enhance the water quality of these recipients and optimize the capacity of wastewater treatment plants (WWTPs), stormwater can be collected in separated sewers, discharging only the urban runoff to the recipient (Pálfy et al., 2017). In this context of rethinking the water management of urban areas, potential cross-contaminations across different compartments can occur, posing a risk for the environment, especially if water is subjected to multiple (re)uses (e.g. water from the recipient used for crop irrigation). Hence, there is a strong need for tools capable of supporting stakeholders towards a wiser and safer use of water resources, to ensure long-term resilience, stability, sustainability and security of the society with regard to water (re)use.
In this work, an integrated model was developed to simulate the fate and associated risk of hazardous contaminants in a cascade water reuse system, located in the city of Milan. The model allows the evaluation of the feasibility of future water management strategies based on the risk assessment.

MATERIALS AND METHODS

The case study, summarized in Figure 1, focuses on the Milan urban area, evaluating the impact of the potential re-opening of an important water canal inside the city to upgrade the historical waterways ("Navigli"). This would allow the re-connection of the urban area with the southern-most agricultural peri-urban area, ensuring a more sustainable energy supply, requalifying an agricultural reserve and revitalizing the historic waterway.

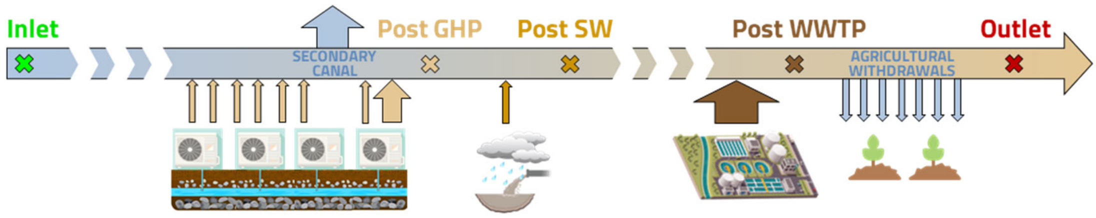

Figure 1. Schematic representation of the waterway, with inputs and outputs. The width of the arrows is an indication of the annual average flowrate. The reconnection allows the inlet to connect with the WWTP.

Within this context, the re-connection infrastructures would be used as a recipient for the various discharges: i) water withdrawn by Groundwater Heat Pumps (GHP), ii) stormwater (SW) collected in a separate sewer system, and iii) downstream to the city, also the contribution of a WWTP effluent. Finally, the recipient delivers the water for crop irrigation. The last part of the waterway (WWTP effluent + crop irrigation) is currently already present.
The fate of commonly occurring micropollutants (MPs) in the different water sources in the case study was predicted adopting the Integrated Urban Wastewater and Stormwater (IUWS_MP) model library (Vezzaro et al., 2014) in the software WEST (DHI A/S, Denmark). The considered MPs were the most detected in all water sources of the area of interest: (i) PFOA and PFOS, that were found in all water sources, with groundwater being the most polluted source, and (ii) pyrene that is largely found in stormwater runoff. Surface water and groundwater concentrations, representing respectively the quality of the INLET point and the discharge of the GHP, were gathered from measurements performed in the last eight years by the regional environmental agency (ARPA Lombardia). WWTP effluent concentrations were both provided by the operating water utility and gathered from Castiglioni et al. (2018). Urban stormwater concentrations were not available for the case study, thus, representative values were gathered from Mutzner et al. (2022). MP concentrations used as inputs to the model are summarised in Table 1.

The model considers multiple dynamics in boundary conditions and stress factors over a 1-year period (temporal dynamic of energy demand, rain events, agricultural practices, different types of contaminants, and change in yearly rain pattern due to climate change). Model simulations were used to assess the environmental risk associated to the presence of the selected micropollutants in the recipient. Both chronic and acute risks were assessed in terms of Risk Quotient (RQ), that is the ratio between MPs concentrations and their reference values, chosen from the available regulations (Table 1), respectively as Annual Average Environmental Quality Standard (AA-EQS) and Maximum Admitted Concentration (MAC-EQS). The acute and chronic risks were evaluated in five monitoring points of the waterway in correspondence with different discharge points, as shown in Figure 1: (i) INLET represents the surface water upstream Milan city; (ii) POST_GHP is right after the discharge of the groundwater used by GHPs; (iii) POST_SW is located right after the discharge of the separate sewer, just downstream Milan city; (iv) POST_WWTP is right after the discharge of the WWTP effluent, where the withdrawals for irrigation purposes start; (v) OUTLET is at the end of the waterway, before entering the Lambro river. The chronic risk for PFAS was calculated in PFOA equivalents.

Table 1. MPs total concentration in the different water sources used as model inputs.

	Surface water	Groundwater	Urban Stormwater	WWTP effluent	AA-EQS	MAC-EQS
	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L
PFOA	2.5	15	16	12	4.4*	290**
PFOS	0.5	19	12	2		36,000***
Pyrene	2.3	1.3	145	1	4.6****	23****

* EU COMMISSION, 2022.
** Norman database
*** European Parliament, 2016
**** Miljøministeriet, 2023

Six scenarios were defined to understand the contribution of each source on the resulting environmental risk:

0. **B (Baseline)**: INLET (2 m^3/s) flowing to the secondary canal (1.99 m^3/s), presence of WWTP effluent (4 m^3/s in dry-weather), agricultural withdrawals
1. **B+GHP**: additional flow of water coming from the discharges of GHPs in the re-connection, with seasonal fluctuation (up to 5.8 m^3/s)
2. **B+GHP+SS08**: additional flow from separated sewer conveying stormwater from 8 km^2, reducing the WWTP catchment area
3. **B+GHP+SS24**: additional flow from separated sewer conveying stormwater from 24 km^2, reducing the WWTP catchment area
4. **B+GHP+SS24+CC10P**: climate change scenario extending the B+GHP+SS24 scenario, with the 10th percentile of the predicted rain in the Lombardy region (World Bank Climate Change Portal, SSP2-4.5, reference period: 2040-2059), and the 10th percentile of MP concentration gathered from literature data (Mutzner et al., 2022)
5. **B+GHP+SS24+CC50P**: climate change scenario extending the B+GHP+SS_24 scenario, with the 50th percentile of the predicted rain in the Lombardy region (World Bank Climate Change Portal, SSP2-4.5, reference period: 2040-2059), and the 50th percentile of concentration gathered from literature data (Mutzner et al., 2022).
6. **B+GHP+SS24+CC90P**: climate change scenario extending the +SS_24 scenario, with the 90th percentile of the predicted rain in the Lombardy region (World Bank Climate Change Portal, SSP2-4.5, reference period: 2040-2059), and the 90th percentile of concentration gathered from literature data (Mutzner et al., 2022).

For climate change scenarios (4-6 above) the inlet flowrate of the waterway was reduced by 5%, as reported for the specific canal of the case study by Abily et al. (2021). For these scenarios, only pyrene impact was evaluated.

RESULTS

PFOA and PFOS did not show exceedance of the acute environmental risk threshold, showing maximum concentrations equal to 14 and 16 ng/L, respectively, along the year and across the various monitoring points. However, the chronic environmental risk was greater than 1 (Figure 2) also in the B scenario after the discharge of the WWTP effluent. For this scenario, the predicted result was compared with the measurements available for the OUTLET monitoring point. The model predicts an average concentration equal to 13.2±1.25 ng/L for PFOA and 3.6±1.00 ng/L for PFOS, while the measurements are equal to 15±6.2 ng/L for PFOA and 6±3.2 ng/L for PFOS.
When looking at the other scenarios, a higher chronic environmental risk is present with GHP and the separated sewer, at the POST_GHP and POST_SW monitoring points, with GHPs increasing significantly the risk (RQ values from <1 up to 10).

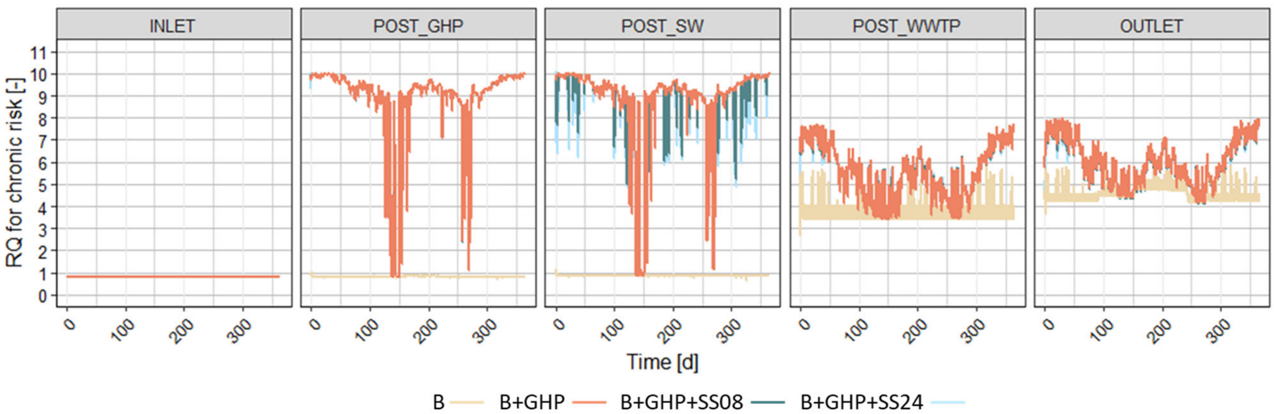

Figure 2. RQ for chronic environmental risk for the sum of PFOA and PFOS in PFOA equivalents, in every monitoring point for some of the scenarios.

The main contribution of PFAS is given by the WWTP effluent in the B scenario, especially in the wet-weather days. When GHPs are considered, their contribution determines a higher concentration in the waterway and hence a higher risk, which is lowered by the dilution effect by the WWTP effluent. The strong variability in the locations POST_GHP and POST_SW refers to the period when GHP are less/not in use (spring and fall) and when SW is released in the waterway. When GHPs are not in use, the risk lowers down to an acceptable level (RQ<1). SW discharges determine a reduction in the risk due to the dilution of the water inside the waterway with less polluted water with respect to PFOA and PFOS.

This chronic risk assessment was performed using as a reference the suggested values of the revision of the European Water Framework Directive (4.4 ng_{PFOAeq}/L, EU Commission, 2022). However, there is still a large uncertainty on these compounds and the effect they pose to ecosystems, which is reflected in the reference values. Furthermore, the limit for the sum of PFAS in drinking water is equal to 100 ng/L, which is 20 times greater than the limit for surface water. A possible strategy to mitigate the risk to the proposed AA-EQS could be the implementation of quaternary treatments at the WWTP, using for example granular activated carbon adsorption, which was shown to be rather efficient on removing specific PFAS from water (Cantoni et al., 2021). The same treatment could be used for groundwater, before discharging water withdrawn by GHPs.

Differently from PFOA and PFOS, which can be considered ubiquitous MPs, the main source of pyrene was found to be urban water runoff. Hence, higher pyrene concentrations are expected in surface water during wet weather only at the locations POST_SW and POST_WWTP, where stormwater is discharged, and subsequently at the OUTLET. In the B scenario, the model predicted at the OUTLET monitoring point an average concentration of 2.2±1.70 ng/L, while the measured concentrations were 5.0±5.9 ng/L. In the B and B+GHP scenarios, the chronic risk (Table 2) is below the threshold of 1 in all of the monitoring points, while in the B+GHP+SW scenarios, the POST_SW point is the most critical one, only when the separated sewer serves a larger area (B+GHP+SW24). For climate change scenarios, the scenario B+GHP+SS24+CC90P displays the highest values of chronic risk.

Table 2. Chronic RQs for pyrene at each monitoring point and scenario. The RQ values exceeding the threshold of 1 are highlighted in red.

RQ CHRONIC	**INLET**	**POST_GHP**	**POST_SW**	**POST_WWTP**	**OUTLET**
B	0.5	0.3	0.3	0.5	0.5
B+GHP	0.5	0.3	0.3	0.4	0.4
B+GHP+SW8	0.5	0.3	0.8	0.6	0.5
B+GHP+SW24	0.5	0.3	**1.1**	0.7	0.7
B+GHP+SW24+CC10P	0.5	0.3	0.3	0.4	0.4
B+GHP+SW24+CC50P	0.5	0.3	**1.2**	0.8	0.7
B+GHP+SW24+CC90P	0.5	0.3	**12.0**	**5.9**	**4.2**

As to the acute risk (Figure 3), no exceedances are shown in the B and B+GHP scenarios, and no exceedances are present at the INLET and POST_GHP monitoring points in all scenarios.

To understand in detail the exceedances of the MAC-EQS value when the sewer is separated and climate change is considered, Figure 3 shows the number of hours per month exceeding the threshold of 23 ng/L (Table 1) at each monitoring point and scenario. For climate change scenarios, acute risk is higher when 50th and 90th percentile of rain and concentrations are used (B+GHP+SW24+CC50P and B+GHP+SW24+CC90P).

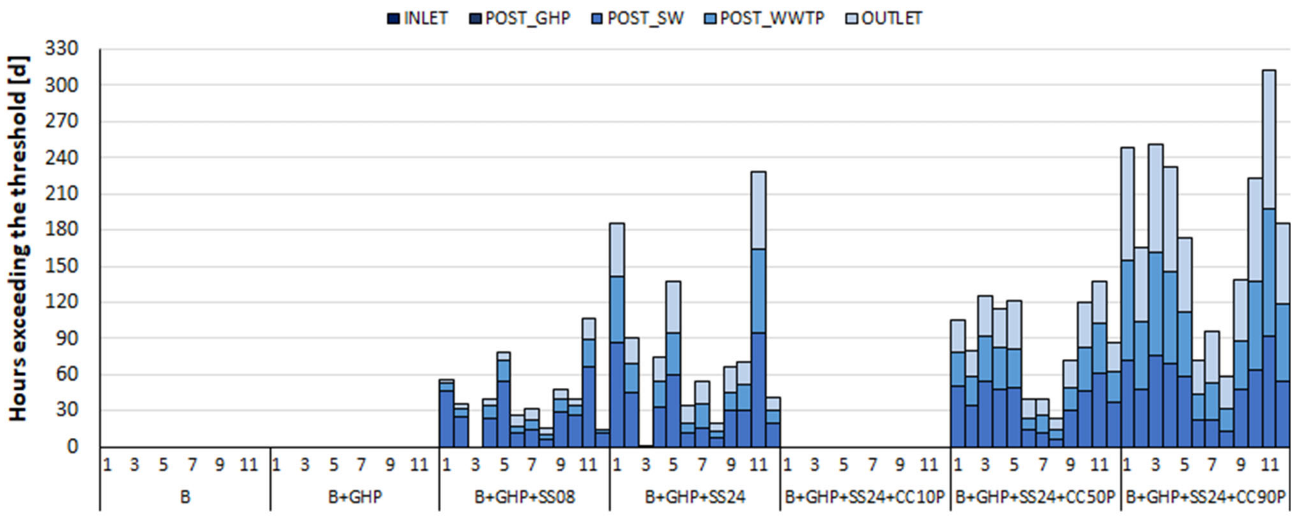

Figure 3. Number of hours per month exceeding the threshold of the acute risk for pyrene (MAC-EQS in Table 1) in each monitoring point, depending on the scenario.

When using 10th percentile of rain and concentration, no exceedances were observed. In a climate change perspective this means that high uncertainty is present on the possible environmental risk, which results to be highly dependent on both rain patterns and concentration levels, which are also somehow dependent on the dry-weather periods between two rain events. Actually, the B+GHP+SW24+CC10P and B+GHP+SW24+CC90P can be considered as representative of the possible extreme scenarios (best- and worst-case). The highest number of hours per month above the limits resulted to be in November (116 hours) at the OUTLET monitoring point for the worst-case scenario (B+GHP+SW24+CC90P). This analysis also highlights how winter months are more critical with respect to the other months independently from the scenario. This is due to the climate change projections, that forecast an increase in rain intensity (mm/month) in the winter months for the Lombardy region.

CONCLUSIONS

The developed model represents a novel tool to predict the fate of micropollutants in complex urbanised areas where water scarcity can be a severe factor, thus water could be subjected to multiple (re)uses. The model can support decision-makers in evaluating the impact of future water reuse practices, considering different factors, and allowing predictions for climate change scenarios, even under high uncertainty. The results presented in this study highlight the potential risk for emerging contaminants, i.e. PFAS and pyrene, introduced by the reuse of GHP discharges and stormwater discharges. No acute risk is present for PFAS, but attention should be paid on chronic risk. Pyrene will pose a risk when separated sewer is used with a larger area, but climate change will significantly increase the risk when an increment of rain and concentrations is considered.

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