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RISK ANALYSIS OF PATHOGENIC ORGANISMS DURING SOIL-AQUIFER TREATMENT: APPLICATION TO A COASTAL AQUIFER IN CYPRUS

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Abstract A quantitative microbial risk analysis of Ezousa (Cyprus) Managed Aquifer Recharge (MAR) site is presented herein to evaluate the health risks associated with the pathogenic fraction of three microorganisms: the bacterium *Escherichia Coli* (*E. Coli*), the *Rotavirus* and the protozoan *Giardia duodenalis*. At Ezousa, raw wastewater from the urban area is subject to wastewater treatment followed by soil-aquifer filtration prior reaching the end-users, who are mainly farmers. The removal efficiency standards of wastewater treatment processes are determined according to World Health Organization (WHO) reports, whereas two extreme end-user exposure scenarios are considered. The first scenario refers to a situation commonly encountered in industrialised countries, where farmers use tractors and associated farming equipment and are expected to wear protective gloves during their activities. The second scenario describes farming practices in developing countries, in which tractors and gloves are rarely used. The results suggest that all three pathogens are likely to infect individuals for both exposure scenarios. Regarding Scenario 1, around 25 % of the samples for *E. Coli* exceed the target values, whereas the highest health risks are found for *Rotavirus* and *Giardia*, in accordance with existing reports. As expected, the risk analysis for Scenario 2 provided much higher values for the health parameters compared to Scenario 1, suggesting that all pathogens possess a high risk for human health under the "worst-case" scenario. Finally, the Quantitative Microbial Risk Assessment (QMRA) was used to predict the required microbial removal after subsurface filtration of treated wastewater, in order to meet health-based targets. For *E. Coli,* the total performance requirement for Scenario 1 and Scenario 2 is found to be 5.5 log_{10} and 7 log_{10} units removal, respectively. These values are consistent with the findings of existing reports, suggesting that the removal efficiency of the soil-aquifer passage plays a crucial role under circumstances such as a heavy microbial load or technical failures.

Keywords: risk analysis; farmers; pathogens; waste-water treatment; soil-aquifer treatment

1. Introduction

Manage Aquifer Recharge (MAR) schemes are processes that intentionally recharge water into aquifers for future recovery or environmental benefits. These systems are considered as elegant options to address issues related to water scarcity, such as contamination of water sources, escalating population growth and rapid urbanization. However, the performance of these systems depends on site-specific factors, such as local hydrogeological conditions and source water quality. Hence, it is important to ensure that MAR schemes remain efficient while sustaining a good physicochemical/microbial groundwater quality to avoid health risks from the presence of pathogens and dissolved compounds [1]. Even though protozoa and viruses are considered as more serious threats to human health than bacteria due to their superior resilience under environmental conditions, recent evidence provided by National and European surveillance agencies revealed a significant increase of illnesses due to the presence of pathogenic *Escherichia Coli* in food supplies. It is also considered as an important indicator of the potential presence of fecal pathogens in aquatic environmental media, such as treated wastewater intended for irrigation purposes [2]. QMRA is a useful tool for evaluating the risks caused by such pathogenic organisms and for supporting decision-making related to the microbial safety of water systems, for example MAR practices [3]. Hence, the objective of the present study is to apply QMRA in order to evaluate the health risks in Ezousa MAR scheme associated with three types of microorganisms: *Escherichia Coli* (bacterium), *Giardia duodenalis* (protozoan) and *Rotavirus* (virus). Two exposure scenarios are considered that are commonly associated in wastewater-irrigated fields, whereas the stochastic computations are performed with an R-script developed by KWB [4].

2. Material and methods

2.1. MAR facility

The MAR site of Ezousa is located at the south-western part of Cyprus, around 10 *km* east of Paphos urban area. It has been operational since 2003 based on Soil Aquifer Treatment (SAT) with the aim of providing a water supply mainly for irrigation purposes. Raw wastewater is led from the urban area to Paphos Urban Wastewater Treatment Plant (UWTP). There, the influent is subjected to three main treatment processes: primary sedimentation, secondary (biological) treatment and chlorine dioxide disinfection [5]. Then, the effluent is distributed through pipeline networks to infiltration ponds, from which it percolates to the saturated zone and mixed with the ambient groundwater. In brief, the recharge network consists of five shallow infiltration basins arranged in a series from the coastline to about 8 *km* upstream. Groundwater withdrawal occurs at nine wells, located close to the infiltration basins, called production (or extraction) wells, from which the reclaimed water is extracted and then distributed to the end-users (mainly farmers involved with crop cultivation) through a canal.

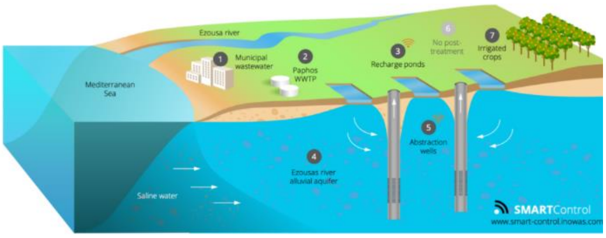

Figure 1. Schematic overview of MAR components at Ezousa SAT system. Sketch can be found in https://smart-control.inowas.com/.

2.2. Exposure scenarios

In this study, we consider the transmission pathway of unintentional ingestion of reclaimed water-saturated soil by farmers in irrigated fields. This is a reasonable scenario since the contaminated soil is likely to transmit pathogenic microorganisms from farmers' fingers to their mouths. The amount of ingested soil has been previously estimated to be less than 100 *mg* per person per exposure event [6]. We have investigated two exposure sub-scenarios: highly mechanized agriculture (Scenario 1) and labour-intensive agriculture (Scenario 2). The former scenario refers to the situation commonly encountered in industrial countries, where farmers use tractors and associated equipment and are expected to wear protective gloves during their activities. The latter scenario describes farming practices in developing countries, in which tractors and gloves are rarely used. Hence, different values for the soil ingestion ranges and for the exposure events are assigned to each sub-scenario (Table 1).

2.3. Quantitative microbial risk assessment

The applied QMRA method can be decomposed into three main stages:

Table 1. : Ingestion ranges and number of events per year for each exposure scnario.

Scenarios	Daily ingestion (litre/day)	Annual exposure events (day/year)
	(min,max,mean)	
Scenario 1	(0.001,0.01,0.005)	100
Scenario 2	(0.01,0.1,0.05)	300

i) Exposure assessment: This stage aims to assess the degree at which the target group is exposed to the wastewater. As a first step, initial concentration values are assigned to each pathogen, which are reduced whenever the wastewater is subjected to a treatment process. A useful parameter to quantify these changes is the log-removal value (LRV), which is an indicator of how efficiently a treatment can remove pathogens:

$$\text{LRV} = log_{10}\left[\frac{Influent\ concentration}{Effluent\ concentration}\right] \qquad (1)$$

ii) Determination of dose-response models: Starting from the raw wastewater collected from the urban area, the dose of the respective agents at which the end-users are exposed to is determined at each treatment process. Subsequently, the probability of an individual to be infected is related with the exposure dose through algebraic expressions, called dose-response models.

iii) Estimation of health impacts: The final stage involves the estimation of the burden of disease associated with each exposure scenario for each of the reference pathogens. The disability-adjusted life year (DALY) is the metric used in WHO guidelines for overall community health burden, hence it is chosen as the performance indicator to allow comparisons to an established health target. According to WHO [7], the wastewater used for irrigation purposes should meet the health outcome target of 10^{-6} for all reference pathogens.

3. Results

In this section, we discuss the main findings of the QMRA of the three specific pathogens for the two exposure scenarios. First, we investigated the health risks based on the literature values of the log-removal fates. Then, we conducted a parametric study in order to predict the microbial removal of the subsurface for meeting health-based targets.

3.1. Scenarios 1 & 2

Table 2 shows the statistical results for DALY indicator for each pathogen, which are compared to the health outcome target of $\mathbf{10^{-6}}$. Both *Rotavirus* and *Giardia* exhibit high health risks since all simulated values exceed the tolerable limits. This is the case especially for the virus, for which the predicted DALY values are almost two orders of magnitudes higher than the health targets. Hence, *Rotavirus* and *Giardia* appear to be more resilient than *E. Coli* to the treatment process, in accordance with the literature. Predictions for *E. Coli* are clustered around the tolerable limit, with 75% being lower than the target value. Regarding Scenario 2, labour-intensive agriculture represents the worst-case scenario, in which labour workers almost never use tractors and gloves. Compared to Scenario 1, the results exhibit a significant increase of the health risks since all predictions are beyond the recommended health values, especially for *Rotavirus*.

Table 2. : QMRA predictions of DALYs per person per year (*pppy*)

Pathogens	Quantiles (%)		
	25	50	75
Scenario 1: Highly mechanized agriculture			
E. Coli	$6.49 \, x \, 10^{-7}$	$8.23 \, x \, 10^{-7}$	$1.06 \, x \, 10^{-6}$
Rotavirus	$2.91 \, x \, 10^{-4}$	$4.03 \, x \, 10^{-4}$	$5.54 \, x \, 10^{-4}$
Giardia duodenalis	$5.36 \, x \, 10^{-6}$	$6.10 \, x \, 10^{-6}$	$7.08 \, x \, 10^{-6}$
Scenario 2: Labour-intensive agriculture			
E. Coli	$2.22 \, x \, 10^{-5}$	$2.60 \, x \, 10^{-5}$	$2.98 \, x \, 10^{-5}$
Rotavirus	$8.94 \, x \, 10^{-3}$	$1.06 \, x \, 10^{-2}$	$1.21 \, x \, 10^{-2}$
Giardia duodenalis	$1.73 \, x \, 10^{-4}$	$1.84 \, x \, 10^{-4}$	$1.98 \, x \, 10^{-4}$

3.2. Health-based performance targets for soil-aquifer passage

According to the previous results, additional treatment is needed to further reduce the pathogens' concentrations so that they meet the health criteria. One way to achieve this goal is to consider an additional treatment process before basin recharge or after extraction (pre-/post-treatment). Both options require additional technical measures. Instead, it is recommended to take advantage of the natural removal capacity of the soil-aquifer passage. The subsurface is widely accepted as an effective barrier for the attenuation of pathogenic microbes [8]. The question we are aiming to answer is: *what should be the minimum log-removal associated to the soil-aquifer passage so that the pathogens concentrations lie within the WHO standards?* To address this question, a parametric study using constant log-values for soil-aquifer passage was conducted. To meet the tolerable disease burden of 10^{-6} DALYs *pppy*, the required LRV of the soil-aquifer passage for *E.Coli*, *Rotavirus* and *Giardia* were calculated for the two exposure scenarios by QMRA. The removal during the soil-aquifer passage was stepwise, increased from 1 to 5 log10 units and at each run DALYs were calculated, while all other QMRA parameters were kept constant. It can be seen that Scenario 2 requires a higher level of treatment performance due to the different exposure parameters (Table 1). The microbial removal of the engineered treatment train for bacteria is given with at least 3 log_{10} (Table 3.4 in [9]). The health-based objective for *E. Coli* (bacteria) is met after an LRV of soil-aquifer passage for Scenario 1 and Scenario 2 at approximately 2.5 log_{10} and approximately 4 log_{10}, respectively (Figure 2). Combined with the microbial removal of the engineered pre-treatment, the total performance requirement for Scenario 1 and Scenario 2 is then 5.5 log_{10} and 7 log_{10} units, respectively. Similarly, the overall treatment performance can be calculated for the other pathogenic microorganisms. The total treatment performance for viruses for Scenario 1 and Scenario 2 is then approximately 4.7 log_{10} and 6.2 log_{10} units, respectively. The total treatment for protozoa for Scenario 1 and Scenario 2 is then approximately 3.2 log_{10} and 4.8 log_{10} units, respectively. These values appear to be broadly consistent with the treatment goals of Alcalde-Sanz and Gawlik [10].

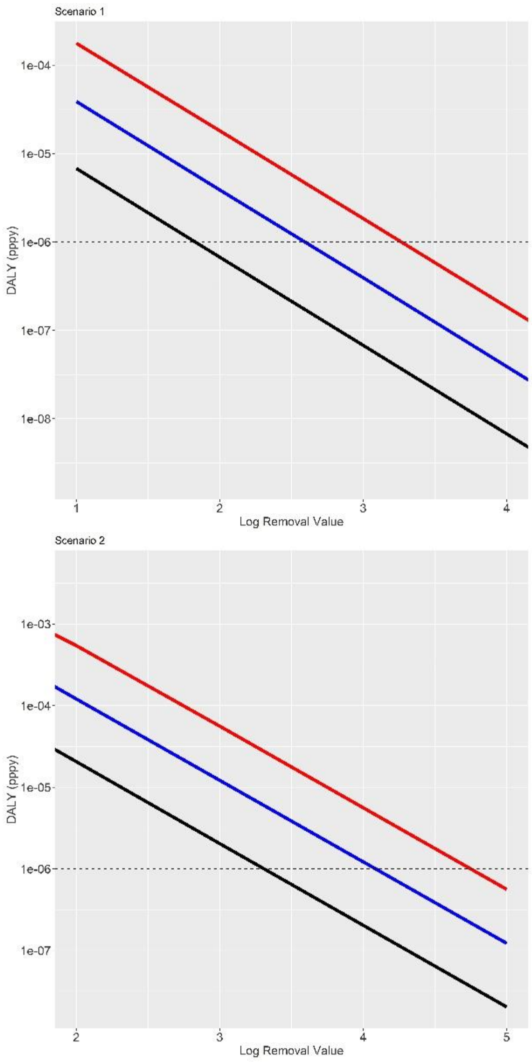

Figure 2. Calculated LRV to meet health-based targets. *Top*: Scenario 1. *Bottom*: Scenario 2. Blue line denotes *E. Coli*, black line denotes *Giardia* and red line denotes *Rotavirus*. Horizontal dashed line denotes the health target 10^{-6} DALYs pppy.

4. Conclusions

We have applied a QMRA to Ezousa MAR scheme in order to evaluate the health risks associated with three indicator pathogens: *E. Coli*, *Rotavirus* and *Giardia duodenalis*. The raw wastewater is typically subjected to four treatment processes, namely primary, secondary, chloride dioxide and soil-aquifer passage, until it reaches the end-users (farmers and labour workers). Due to the lack of local data, literature values are assigned to the log-removal reductions associated with each treatment process. As a result, the current risk approach is applicable to other MAR sites that involve the same treatment processes. The risk analysis of Scenario 1 suggests that none of the pathogens meet the health criteria without the need of additional treatment, whereas both *Rotavirus* and *Giardia* possess high disease risks. Regarding *E. Coli*, around 25 % of the samples exceed the recommended values, suggesting that further treatment is required. As expected, the risk analysis for Scenario 2 provided much higher values for the health parameters compared to Scenario 1, suggesting that all pathogens possess a high risk for human health. Due to the high uncertainty of the LRV associated with the soil-aquifer passage, additional computations were performed to estimate what the minimum LRVs of this process should be in order to meet the health-based performance targets. These values are consistent with the findings of existing reports, which also emphasize the significant role of soil-aquifer passage as a hygienic barrier under adverse conditions.

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