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Development of a Decision Support Tool to Assess the Impact of Wastewater Reuse on Downstream Watercourses: STREAM—Support Tool for Reuse Evaluation and Management

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Abstract

Sustainable water management has become one of the main concerns in Europe, with water reuse practices as a key strategy for it. In this framework STREAM was developed, an open-access decision support tool (DST) designed to assess the hydrological, chemical, and agricultural implications of wastewater treatment plant (WWTP) effluent reuse in a real context. The DST simulates the interaction between WWTP effluent composition and the receiving water body in terms of hydrological balance, chemical composition and implications for agriculture. The outputs provide the effects on the ecological status of the river and the potential saving in fertilizers. To generalize system behaviour, a dimensionless ratio between river flow and WWTP discharge (R) is introduced, enabling the interpretation of reuse scenarios in terms of hydrological dominance. The DST was applied to three case studies in Luxembourg representing a range of WWTP capacities and river conditions. Results show that reuse feasibility is governed by the interaction between R and baseline water quality conditions, rather than by flow magnitude alone. Systems characterized by high R values exhibit greater dilution capacity and lower ecological risk, while systems with low R are more sensitive to effluent inputs. These findings position STREAM as a screening-level analytical framework that complements existing techno-economic DSTs, supporting early-stage decision-making in water reuse planning, particularly in contexts with limited data available.

Keywords: ecological impacts; decision support tool; nutrients recycling; reclaimed water; water reuse



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1. Introduction

The European Water Resilience Strategy identifies water reuse as a key measure to improve sustainable water management and reduce pressure on freshwater resources [1]. Water reuse is already widely practised in many arid and water-stressed regions [2,3] where treated wastewater represents an alternative and reliable water source for agricultural irrigation. In addition to supplying water, treated WWTP effluents still contain nutrients such as N and P that can partially satisfy crop requirements [4,5]. Several studies have reported reduced fertilizer demand and improved crop productivity when reclaimed water is used for irrigation [6–8]. Furthermore, water reuse can reduce nutrient discharges to surface waters while providing a dependable water supply throughout the year.

Despite these advantages, wastewater reuse may also have unintended consequences for receiving water bodies. Diverting treated effluents for irrigation reduces the volume discharged into rivers and streams, potentially affecting flow conditions, hydromorphological processes, ecological functioning and pollutant dilution capacity. These effects may be particularly relevant in small watercourses, where WWTP effluents often constitute a substantial proportion of the total flow. Therefore, the implementation of water reuse schemes should be supported by assessments that consider both water quantity and water quality, ensuring that the benefits of reuse are achieved without compromising the ecological status of receiving ecosystems.

Recent review studies have highlighted both the rapid development of decision support tools (DSTs) for wastewater reuse and their current limitations. The reviews by Pasciucco et al., 2022 [9], Renfrew et al., 2024 [10] and Ko et al., 2024 [11] showed that most wastewater reuse DSTs have been designed to support the selection of treatment technologies, reuse schemes, and management alternatives, commonly integrating technical, economic, environmental, and social criteria through approaches such as multicriteria decision analysis (MCDA), analytical hierarchy processes (AHP), life-cycle assessment (LCA), and cost–benefit analysis. Similarly, the review of Integrated Urban Water Management (IUWM) models by Mosleh et Negahban-Azar, (2021) [12], demonstrated that existing tools mainly focus on water supply, wastewater and stormwater management, demand forecasting, and infrastructure planning, while ecosystem services and environmental impact assessment remain comparatively underrepresented. Although some of these approaches include water quality indicators, they generally evaluate the performance of the reuse system itself rather than the environmental consequences of reuse practices on receiving water bodies. To highlight the scope and limitations of the main DST approaches identified, Table 1 summarizes their primary objectives and typical outputs.

Table 1. Main DST approaches applied to water reuse.

DST Approach	Objective	Typical Outputs	Limitations
MCDA/AHP	Selection of reuse technologies	Technology ranking, economic and sustainability indicators	Limited consideration of receiving water impacts
LCA	Environmental performance of reuse technologies	Carbon footprint, energy demand, resource use	Indirect assessment of water quality impacts
IUWM	Integrated urban water management	Water quantity and quality simulations	Receiving water impacts not linked to reuse decisions

Consequently, a clear gap was found: very few DSTs explicitly assess the impacts of reuse scenarios on receiving water quality and associated environmental risks. Addressing this gap is crucial to guarantee a safe but also sustainable reuse. To this end, the present study considers three aspects: (1) development of a Support Tool for Reuse Evaluation and Management (STREAM), designed to evaluate the implications of WWTP effluent reuse in agriculture on the quality status of the receiving watercourse, related to changes in flow and nutrient loads; (2) as added value, the tool can also estimate the possible benefits for the crops in terms of fertilizer savings; (3) the STREAM tool will be tested in a case study where three real scenarios of Luxembourg will be evaluated.

Beyond the development of the tool itself, this study proposes a simplified analytical framework based on a dimensionless ratio (R) and an Ecological Status Index (ESI) to interpret the impact of wastewater reuse on receiving waters. This framework is designed for practitioners and decision-makers with basic technical knowledge of water quality

and agricultural water management, enabling rapid evaluation of reuse scenarios and supporting early-stage feasibility assessments.

2. Materials and Methods

2.1. DST Design and Structure

STREAM is conceived as a screening-level analytical framework for the preliminary evaluation of water reuse scenarios, and is implemented through a DST based on Microsoft Excel (Microsoft 365). Figure 1 shows the conceptualization of the DST. The system is designed to process two main input components, the natural water body upstream, representing the background hydrological conditions, and the WWTP effluent with a determined flow and higher pollutant content. The DST simulates the interaction between these two inputs and produces two categories of outputs: (a) possible impacts on the water body, resulting from the dilution capacity, and (b) potential effects on the agricultural activity associated with irrigating with reclaimed water. Computations are based on three main analytical modules:

- Hydrological balance, which quantifies changes in the river flow regime caused by the partial or complete reuse of the WWTP effluent.
- Water quality analysis, which estimates variations in the physical parameters and final pollutant concentrations in the receiving water body. This module also evaluates possible changes in the ecological status according to the WFD by calculating the ESI for key indicators.
- Implications for Agriculture. This module assesses if the WWTP effluent meets the required quality criteria for reuse according to EU Regulation 2020/741 as well as estimating the potential irrigated area based on flow and crop demands. Moreover, it evaluates the potential benefits regarding fertilizer savings, associated with the presence of nutrients in the WWTP effluent.

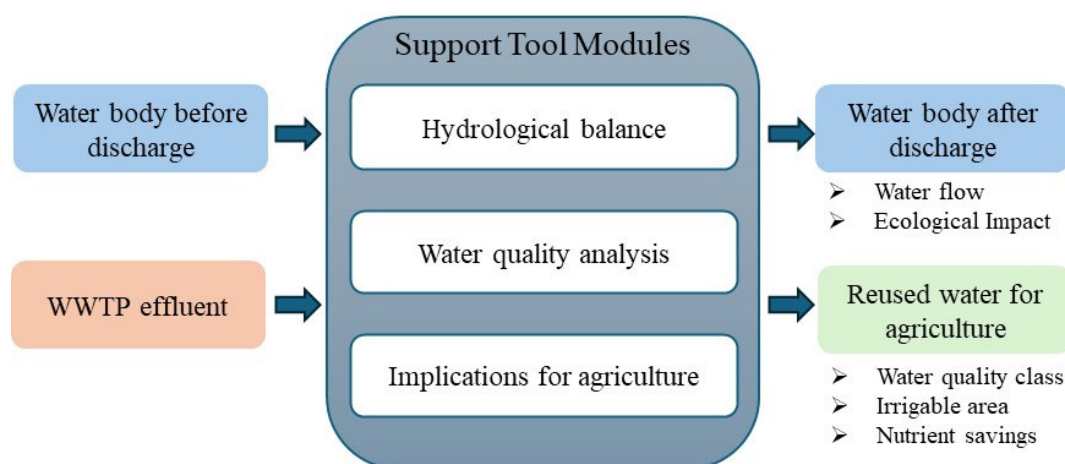


Figure 1. Schematic description of the main components of STREAM.

The conceptual design of STREAM presents some boundaries intended to simplify the calculations while maintaining a realistic representation of the hydrological and chemical processes. For example, return flows from irrigated fields, salinity accumulation in soils irrigated with WWTP effluent as well as the possible bioaccumulation of micropollutants are not included in this assessment. These and other factors related to wastewater reuse must be assessed through the risk assessment defined by the EU [13]. Such simplifications are consistent with the intended use of STREAM as a DST for early-stage evaluations, when detailed datasets or advanced modelling results are often unavailable. A key advantage of

this approach is that STREAM uses parameters that are commonly monitored in WWTPs and receiving waters as part of routine operational and regulatory programmes. As a result, preliminary assessments can be performed without requiring additional monitoring campaigns or specialised investigations. STREAM can be used to identify potentially suitable or unsuitable scenarios and to compare alternative management options; however, it is not intended to predict detailed pollutant fate and transport processes, temporal dynamics, ecological responses, pathogen-related health risks or long-term impacts. These aspects should be addressed through more comprehensive risk assessments and mechanistic modelling approaches during subsequent stages of project development when required.

2.2. Selection of Key Parameters and Orientation Values

The proposed DST relies on a set of orientation values to evaluate the suitability of wastewater reuse scenarios and their potential impacts on receiving waters. For the case study application, these values were derived from the Luxembourgish regulatory framework and environmental objectives aimed at protecting surface waters. Luxembourg provides a suitable scenario because many of its watercourses are small streams where treated WWTP effluents may constitute a significant fraction of river flow, making them potentially sensitive to water diversion and changes in water quality. Nevertheless, the orientation values can be modified by the user, allowing the DST to be easily adapted to different regulatory and environmental contexts.

2.2.1. Hydrological Balance

Hydromorphological conditions are closely linked to physicochemical quality parameters of surface waters; therefore, any alteration in the discharge regimes can significantly influence these characteristics. To mitigate negative impacts, the German Federal/States Work Group for Water (LAWA in German) proposed the concept of minimum water orientation value (MOV; with units $\text{L s}^{-1} \text{ km}^{-2}$) as an indicator to prevent high sediment accumulation or long-term drying of surface waters. The MOV must be determined for each specific case study. However, as a general guideline LAWA [14] recommends that water abstraction should not exceed 50 L s^{-1} , and the average annual extraction (Q_e , in $\text{m}^3 \text{ a}^{-1}$) should not exceed one third of the river's mean low flow (MNQ, in $\text{m}^3 \text{ a}^{-1}$). These criteria were used as basis for the hydrological analysis in this study.

2.2.2. Water Quality Analysis

The Luxembourgish Third Management Plan of the WFD [15] reports the recommended values of the main parameters (see Table 2) required to maintain water bodies at or above the transition threshold between “good” and “moderate” ecological status. Compliance with these threshold values is essential to preserve both the biotic and the abiotic integrity of the aquatic ecosystem and were taken for reference in the computations.

2.2.3. Implications for Agriculture

The tool includes a selection of representative crops based on data from the Institut national de la statistique et des études économiques du Grand-Duché de Luxembourg (STATEC). According to this source, wheat, maize, barley, triticale and rape are the most harvested crops per hectare, thus, they were selected for the purpose of the tool. Each crop has specific water requirements, with $40 \text{ m}^3 \text{ ha}^{-1} \text{ d}^{-1}$ for wheat, 39 for maize, 40 for barley, 40 for triticale and 43 for rape [16]. While this study focuses on a limited number of crops for demonstration purposes, the framework can be extended to other crop types including the required and specific crop data.

Regarding nitrogen-based substances, Article 6 of the Grand-Ducal Regulation of 24 November 2000 on the use of nitrogenous fertilizers determines that the quantity of

organic fertilizer applied per year and per hectare must not exceed 170 kg of N, except in the case of protein crops and pure legume crops for which the limit is 85 kg of N in agriculture. This maximum value was assumed in this study for all crops as a fertilizer requirement. However, there is no regulation for P_2O_5 , K_2O and MgO ; thus, reference values are used (see Table 3). In practice, fertilization is mainly needed from February to May, with additional smaller applications in July and August depending on crop development and nutrient demand.

Table 2. Orientation values for the main physicochemical quality components that define the transition between “good” and “moderate” ecological status in the different surface waters in Luxembourg.

	River Type		
	I/II, III	IV, V	VI
Temperature	20	20	25
Oxygen * ($mg\ L^{-1}$)	8	7	7
BOD ₅ ($mg\ L^{-1}$)	3	3	6
TOC ($mg\ L^{-1}$)	7	7	7
Chloride	200	200	200
pH	6.5–8.5	7.0–8.5	7.0–8.5
o- PO_4 -P ($mg\ L^{-1}$)	0.7	0.7	0.7
P total ($mg\ L^{-1}$)	0.1	0.1	0.1
NH_4 -N ($mg\ L^{-1}$)	0.1	0.1	0.1
NH_3 -N ($mg\ L^{-1}$)	1	2	2
NO_2 -N ($\mu g\ L^{-1}$)	30	50	50
NO_3 ($\mu g\ L^{-1}$)	25	25	25

Notes: * Minimum year⁻¹. For the rest of the parameters, the value refers average year⁻¹. River classification: Types I/II, III correspond to the rivers of the Oesling region. Types IV/V correspond to rivers of the Gutland region. Type VI corresponds to major lowland rivers.

Table 3. Reference yields and fertilization standards for P, K and Mg for the most conventional crops in Luxembourg. Adapted from Sinaj et al., 2017 [17].

Crop	P_2O_5 ($kg\ ha^{-1}$)	K_2O ($kg\ ha^{-1}$)	MgO ($kg\ ha^{-1}$)
Wheat	60	100	25
Barley	60	115	25
Rye, Triticale, Spelt	65	120	25
Rape	84	174	30
Maize	126	243	54

WWTP effluent parameters are determined as P, Mg, and K concentration, but the fertilizer requirement of the crops is given in P_2O_5 , K_2O and MgO , thus, the values were converted to the corresponding oxide forms to ensure consistency with the legislation. (Supplementary Materials Nutrients conversion).

2.3. Computation

STREAM performs dynamic calculations through a series of embedded Excel formulas that automatically update the outputs based on the user selections and inputs.

2.3.1. Impacts of Reuse in the Receiving Waters

The permissible flow of WWTP effluent available for reuse is determined based on the hydrological constraint described in Equation (1). The median is used instead of the average to avoid extreme values in the dataset caused by unforeseen weather events. Scenarios that

do not comply with Equation (1) are considered infeasible and should be excluded from further analysis.

$$Q_e \leq \frac{1}{3} \cdot MNQ \quad (1)$$

It is recommended to study the river flows during the dry season or summer period, when agricultural water demand increases while flow is reduced due to the lower rainfall, meaning that WWTP effluent represents a larger fraction of the total flow. This period stretches from April to September.

The second step of the computation involves determining the quality class of the WWTP effluent according to EU Regulation 2020/741. If data for *E. coli*, total suspended solids (TSS), and biochemical oxygen demand (BOD₅) are provided, the program compares these values with the threshold limits. Based on this comparison, the WWTP effluent is automatically assigned to one of the quality classes A, B, C, D, or “No class” if the criteria are not met. Turbidity was excluded as a classification parameter as the regulation specifies a limit only for quality A, making it non-discriminatory for other categories. Validation monitoring requirements, including log-reduction for other pathogens specified in the Regulation, are not considered because these data are not routinely available for most WWTPs and fall outside the scope of a screening-level assessment.

The key component of the output section concerns the physicochemical status of the receiving river. The orientation values for the reference parameters are defined in detail in the Third River Basin Management Plan [15], being different according to the river type, which must be specified by the user. To estimate the expected concentration of a parameter in the receiving water, which will be used to determine the ESI, two approaches are available: (1) When the river quality monitoring station is located upstream of the WWTP (the user selects “Upstream” as option); and (2) when the monitoring station is located downstream of the WWTP (selecting “Downstream” as option).

To facilitate interpretation and enable comparison across different systems, the parameter R is introduced as a governing variable controlling system behaviour across reuse scenarios (Equation (2)):

$$R = \frac{MQ}{Q_W} \quad (2)$$

where MQ is the mean flow of the receiving body (L d^{−1}) and Q_W is the seasonal average of treated wastewater that is discharged into the receiving water (L d^{−1}). This ratio represents the relative dominance of natural river flow versus WWTP effluent discharge, with low values indicating conditions dominated by the effluent and high values indicating conditions dominated by the river. While the MNQ defines the maximum allowable extraction from a hydrological perspective, R reports the resulting impact through dilution processes.

Using this formulation, the concentration after mixing is calculated as a mass balance according to Equation (3):

$$C_a = \frac{R \cdot C_r + C_W}{R + 1} \quad (3)$$

where C_a is the concentration of a physicochemical parameter in the receiving water after WWTP effluent discharge, C_r is the concentration in the receiving water upstream of the WWTP in (mg L^{−1}), and C_W the concentration of the physicochemical parameter in the WWTP effluent (mg L^{−1}).

For the stations located downstream, the monitored values already represent the mixture of river water and treated effluent. Thus, it is necessary to estimate C_r (Equation (4)) and subsequently use that value in Equation (3) to obtain C_a.

$$C_r = \frac{C_a \cdot (R + 1) - C_W}{R} \quad (4)$$

Once C_a is calculated for all physicochemical components, as shown in Table 2, the ESI can be estimated according to Equation (5):

$$ESI = \max_i \left(\frac{C_{a,i}}{\text{Orientation value}_i} \right) \quad (5)$$

where $ESI = 1$ represents the threshold of ecological compliance, $ESI < 1$ indicates compliance with good ecological status and $ESI > 1$ indicates moderate ecological status.

As pH is a logarithmic measure rather than a concentration value, it cannot be directly used in the mass balance calculations. It should be converted to H^+ ($H^+ = 10^{-pH}$) which allows to use it as a concentration parameter for subsequent calculations.

2.3.2. Evaluation of Reclaimed Water for Irrigation in Agriculture

The second part of the output section comprises the agricultural application of the tool. Depending on the selected crop type, the potential for irrigation with WWTP effluent changes. The irrigable area per day indicates the cultivated surface that can be potentially watered with reclaimed water for that specific crop, and is calculated using Equation (6):

$$I_{\text{area}} = \frac{Q_W \cdot \frac{R_{\text{water}}}{100}}{Q_{\text{req.}}} \quad (6)$$

where I_{area} is the irrigable area in ha, R_{water} the percentage of WWTP effluent that is intended for reuse (%) and $Q_{\text{req.}}$ the specific water requirement for the crop in $\text{m}^3 \text{ha}^{-1} \text{d}^{-1}$. In this calculation Q_W is in $\text{m}^3 \text{d}^{-1}$.

The nutrient savings through water reuse (N_S) represent the percentage of fertilizer demand that can be supplied by nutrients contained in the WWTP effluent. The value is calculated according to Equation (7).

$$N_S = \frac{Q_W \cdot R_{\text{water}} \cdot N_W}{N_{\text{req.}} \cdot I_{\text{area}}} \cdot 100 \quad (7)$$

where N_W is the concentration in the WWTP effluent of the nutrient under study in kg m^{-3} , and $N_{\text{req.}}$ the nutrient requirements of the crop according to Table 3.

2.4. Case Studies

The testing of STREAM was based on two main datasets provided by official administrative entities from Luxembourg. The Syndicat Intercommunal de Dépollution des Eaux Résiduelles du Nord (SIDEN) is responsible for collecting and treating wastewater generated in 35 communes in northern Luxembourg. They provided the first dataset, containing data regarding the treated flow in the WWTPs and the physicochemical characterization of the WWTP effluents before discharge.

The locations were chosen to represent a wide range of cases, including both large and small facilities operating under different river flow conditions. The selection is shown below:

- Bleesbruck WWTP (130,000 Population Equivalent (PE)). The facility consists of a first mechanical pre-treatment followed by a classical activated sludge biological treatment with longitudinal clarifiers. During the most recent modernization, no disinfection step was implemented; however, space has been reserved for a future quaternary treatment. Sludge is treated on site through anaerobic digestion, and the resulting

biogas is energetically valorized. The treated wastewater is discharged into the Sûre river, with a MQ of $27.5 \text{ m}^3 \text{ s}^{-1}$.

- Stolzembourg WWTP (5000 PE). Considered a medium-size facility in the Luxembourg context, the main treatment is based on a biological combined system (BIOCOS) consisting of an activated sludge process integrating carbon and nutrient removal with a secondary clarification. The generated sludge is transported to the Bleesbruck WWTP for further processing and dewatering. The effluent is discharged into the Our River—a medium-sized river tributary of the Sûre—with a MQ of $9.3 \text{ m}^3 \text{ s}^{-1}$.
- Consdorf WWTP (4000 PE). The treatment comprises a mechanical pre-treatment followed by a BIOCOS. Sludge can be dewatered on site using a mobile dewatering unit or transported to the Bleesbruck WWTP for further treatment. The final effluent is discharged into the Consdorferbach stream, with a MQ of $0.093 \text{ m}^3 \text{ s}^{-1}$.

The Water Management Authority (Administration de la Gestion de l'Eau (AGE)) is responsible for a sustainable and integrated management of Luxembourg's water resources ensuring their protection. The second dataset containing information on the key parameters of receiving rivers was provided by them. A summary of both datasets is presented in Table 4.

Table 4. Annual average values of the most relevant parameters used to determine the impacts of WWTP effluent discharge.

	WWTP			Receiving Water Bodies		
	Bleesbruck	Stolzembourg	Consdorf	Sûre	Our	Consdorferbach
<i>E. coli</i> (CFU 100 mL ⁻¹)	30,629	26,000	27,500	N.A.	N.A.	N.A.
Temperature (°C)	12	12	9.5	11.5	10.5	9
pH	8	7.5	8	8	8	8
BOD ₅ (mg L ⁻¹)	2.5	3	3	1.5	1	1
K (mg L ⁻¹)	12.5	13.5	15	N.A.	N.A.	N.A.
Mg (mg L ⁻¹)	25	8.5	7	N.A.	N.A.	N.A.
PO ₄ (mg L ⁻¹)	1	3	1.5	0.11	0.02	0.25
P total (mg L ⁻¹)	0.5	1.45	0.75	0.2	0.06	0.29
NH ₄ -N (mg L ⁻¹)	1.9	0.5	0.4	0.12	0.03	0.05
NO ₂ -N (mg L ⁻¹)	0.2	0.1	0.1	0.5	0.1	0.3
NO ₃ -N (mg L ⁻¹)	2.8	1.2	3.2	4.5	3.5	7.7
N total (mg L ⁻¹)	5.5	2	4.5	N.A.	N.A.	N.A.

Note: N.A.: Not available.

For the three scenarios, the DST analyses the impact on the water body and for agriculture during summer and winter to represent the dry and wet season. An effluent reuse rate of 50% was assumed for all scenarios, and wheat was selected as the most representative crop.

3. Results

3.1. DST Description

STREAM is an open-access tool hosted in the Zenodo repository [18]. The tool brings together hydrological, physicochemical, and agricultural information to support the evaluation of different wastewater reuse scenarios.

The analysis is based on four categories of information: river hydrology, WWTP effluent characteristics, receiving water quality, and crop requirements. Following the computational procedures described in Section 2.3, these datasets are combined to evaluate the effects of wastewater reuse under different hydrological and seasonal conditions. Hydrological parameters are used to characterize the relationship between natural river flow and

WWTP effluent discharge through the parameter R , which determines the dilution capacity. Physicochemical data are subsequently used to evaluate compliance with environmental quality objectives and the ecological status.

The tool considers 17 WWTP effluent parameters (Figure S1a). Among them, 12 physicochemical parameters are used for ecological status assessment, while Mg and K are included to estimate the potential recovery of nutrients through agricultural reuse. In addition, *E. coli* concentrations are used to determine the reclaimed-water quality class according to EU Regulation 2020/741 and, consequently, the suitability of the treated effluent for different reuse applications. The physicochemical status of the receiving water is assessed using the orientation values corresponding to the selected river type. The DST also accounts for the location of the monitoring station relative to the WWTP discharge point, allowing the appropriate application of the assessment procedures described in Section 2.3.

In parallel, agricultural reuse is evaluated through specific crops requirements. The selected crop determines both irrigation demand and nutrient requirements, allowing the assessment of irrigation potential and fertilizer substitution. This component complements the environmental assessment by quantifying the potential benefits associated with wastewater reuse in agriculture.

The outputs generated by STREAM (Figure S1b) are organized into two complementary categories. The environmental assessment includes the hydrological balance results, the receiving water quality indicators, and the ESI, which provides an integrated measure of compliance with the selected environmental objectives. The agricultural assessment includes the reclaimed water quality classification, the irrigation potential, and the fertilizer savings. Together, these parameters provide a comprehensive overview of the trade-offs between wastewater reuse benefits and potential impacts on receiving waters, supporting the identification of environmentally acceptable and agriculturally beneficial reuse scenarios. The generated indicators constitute the basis of the decision support process implemented in STREAM.

The tool supports decision-making through the direct comparison of the calculated concentrations of indicators with the regulatory and ecological reference values. For each scenario, a parameter is considered acceptable when its calculated value remains below the orientation values ($ESI < 1$) defining good ecological status for the selected river type and hydrological condition (indicated by a green mark in the interpretation row). Scenarios in which calculated indicators meet these criteria are classified as environmentally acceptable. When one or more indicators exceed the reference value (meaning $ESI > 1$, indicated by a red mark in the interpretation row), the scenario is considered unsuitable without modification.

In such cases, users are expected to revise key inputs, particularly the fraction of effluent diverted for reuse. By progressively adjusting that fraction, users can identify the maximum reuse percentage that maintains all indicators below the reference values. Within this process, variations in reuse fraction directly influence the hydrological ratio R and consequently the ESI, linking user-defined scenarios with system response. In this way, the tool not only indicates whether a given reuse fraction (e.g., 50%) is environmentally safe or not, but also allows users to determine the highest permissible reuse limit under specific seasonal and hydrological conditions. Among environmentally acceptable scenarios, agricultural reuse indicators, such as reclaimed water quality class, irrigation potential, and fertilizer savings, can then be compared to identify configurations that maximize agricultural benefits while maintaining compliance with environmental references. This interactive evaluation enables users to test several reuse scenarios to choose the most suitable option for the final user that both safeguards downstream water quality and supports resource recovery.

3.2. Application of the DST

3.2.1. Bleesbruck WWTP Case

Bleesbruck WWTP is the largest facility among the three selected for STREAM demonstration. Due to the high treatment capacity of Bleesbruck WWTP and the stability and high flow of the Sûre River, this WWTP showed potential for full-year reuse capacity. The system even allows 100% of reuse in both summer and winter, without exceeding the 1/3 MNQ extraction limit. These conditions correspond to high values of R , indicating a river-dominated system with an expected high capacity to assimilate pollutants.

However, during summer, the background concentrations of P total, NO_2^- and NH_4^+ in the Sûre River are already much higher than the orientation value. This means that the river has limited or no capacity to dilute the inputs from the WWTP, and any discharge would lead to a reduction in water quality. Thus, maximizing the reuse of WWTP effluent is beneficial for improving the ESI.

During winter, background P total and NH_4^+ are lower than in summer, but still high enough to classify the river in a moderate quality status. For this reason, the diversion of WWTP effluent represents a beneficial option for the receiving ecosystem. Although 100% effluent reuse would not improve P total, reusing only 6% would be enough to meet the NH_4^+ target value. This illustrates how small variations in reuse fraction can shift ESI to < 1 for specific parameters.

In recent years, Bleesbruck WWTP has undergone extensive renovations to enhance its treatment capacity but still lacks a post-treatment able to eliminate the remaining pathogens present in the effluent. For a safe reuse, the effluent must be purified by an additional disinfection step before being used for the farmers. Given the high PE, in a near future the facility will require the implementation of a quaternary treatment to remove microcontaminants (such as pharmaceuticals and personal care products) to comply with the new Urban Waste Water Treatment Directive [19]. Quaternary treatment consists of advanced treatment technologies that in some cases, such as those based on ozonation or UV/ H_2O_2 processes, not only eliminate such contaminants but also provide effective disinfection, enabling the production of high-quality effluent suitable for irrigation in a single process.

As the largest WWTP of those assessed, Bleesbruck offers the greatest potential irrigable area, particularly during the winter season. The effluent provides a notable nutrient supply, covering approximately 50% of the N and 30% of P demand for wheat crops. Moreover, it contains very high concentrations of Mg and K, which exceed crop requirements meaning that no additional MgO or K_2O application would be necessary. However, the excess of ions not absorbed by plants may accumulate in the soil, increasing salinity levels. This phenomenon needs further investigation to prevent soil degradation under long-term irrigation with this effluent.

3.2.2. Stolzembourg WWTP Case

Given the high base-flow of the Our river, water reuse is feasible in both seasons, summer and winter, even at 100%. The extracted volume remains below the 1/3 MNQ threshold, making Stolzembourg a highly favourable case for large-scale reuse. Moreover, R values are also high, confirming that conditions are dominated by the river.

The background conditions of the Our river before the WWTP discharge already comply with the criteria for good ecological status. Due to the high R , changes in the percentage of diverted water produce minimal changes in ESI. However, a limited flow due to the medium size of the WWTP constrains the potential for irrigation. To ensure compliance with EU standards for safe reuse, the treated effluent requires an additional simple disinfection step, such as UV irradiation or chlorination, prior to reuse.

Regarding nutrient content, the effluent provides enough P to meet 100% of the crop demand. In contrast, N availability remains limited, supplying only about 25% or less of the crop nutrient requirement, which indicates a lower potential for savings. As in the Bleesbruck case, the effluent contains high concentrations of Mg and K which may accumulate in the soil and should therefore be considered in risk assessments.

3.2.3. Consdorf WWTP Case

Due to the low flow of the Consdorferbach stream, Consdorf is the most sensitive location to maintain hydrological balance during effluent reuse, corresponding to a system dominated by WWTP effluent, with low R values. According to the 1/3 MNQ rule, 50% of effluent diversion is feasible throughout the year. It should be remarked that in the winter season the flow discharged from the WWTP as well as the river flow are significantly higher than in summer. MNQ is a fixed annual value, this seasonal increase in river flow is not considered for the calculation. Consequently, while a higher reuse percentage would be hydrologically feasible in practice, it is not formally allowed under the existing guidelines.

Consdorferbach stream's baseline conditions do not meet the criteria for a good ecological status. During winter, concentrations of P total and NO_3^- exceed the orientation values, and inputs from the WWTP further elevate these levels, with an ESI value significantly above 1. For this reason, even under a hypothetical 100% effluent reuse scenario, the overall improvement in water quality would remain limited, and the ecological status would not change. In summer, background concentrations of P total and NO_3^- also exceed the orientation values, indicating a persistent nutrient enrichment of the river that can promote oxygen depletion and eutrophication. To ensure compliance with EU standards for safe reuse, the treated effluent requires an additional simple disinfection step, such as UV irradiation or chlorination, prior to reuse.

The potential irrigable area using Consdorf's effluent is smaller than that of larger facilities but comparable to the Stolzembourg case. N loads are moderately high, covering approximately 50% of the wheat demand, being greater than those covered by Stolzembourg WWTP effluent. In contrast, P savings are significantly lower, reaching a maximum of 60% in summer. As in the previous case studies, Mg and K loads are significantly higher than the crop requirements and should be carefully assessed.

The three case studies confirm the ability of STREAM to represent reuse scenarios under realistic conditions. Across all cases, system behaviour is largely driven by the R parameter, which, when combined with the ESI, provides a consistent interpretation of how hydrological conditions influence ecological status.

At the same time, the results show that reuse feasibility depends not only on hydrological constraints but also on the initial condition of the receiving water body. In particular, the baseline ecological status and the selected reuse fraction emerge as key factors controlling the outcome of reuse scenarios.

Together, these findings indicate that STREAM can be used not only as a calculation tool, but also as a practical framework identifying system-specific limitations at an early stage. This makes it particularly relevant for supporting decision-making in water reuse planning, where rapid and transparent assessments are required.

4. Discussion

A wide range of DSTs has been developed in recent years to promote water reuse by enabling an easy evaluation and comparison of scenarios. Most of these tools are focused on treatment technology selection, economic performance or human health protection, while the broader environmental implications of reuse in the receiving ecosystem remain unaddressed.

An example of a powerful DST for technology assessment is Poseidon, developed to facilitate pre-feasibility studies identifying the best treatment train from a multi-criteria perspective, considering water quality parameters, treatment processes and cost [20]. Including the agricultural side, RWRM [21] was conceived to select a cost-effective treatment train that meets both regulatory standards and crop requirements. In both cases, the emphasis remains on techno-economic implications rather than evaluating the environmental impacts of the reuse practice itself. The MULTI-ReUse tool [22] constitutes an important step forward by incorporating the ecological and social dimensions into the assessment framework, providing a global view of the reuse scenario. The Environmental Protection Agency of the United States (EPA) has developed a Water Quality Analysis Simulation Program (WASP) [23], a mechanistic modelling framework that describes pollutant transport, mixing processes, and inputs from point and non-point sources over time. The level of detail provided by WASP is essential for in-depth regulatory or predictive studies. However, it may not be necessary for preliminary assessments aimed at screening the feasibility of water reuse scenarios. In this context, STREAM is positioned as an analytical framework for situations where only limited data are available, whereas mechanistic models such as WASP remain necessary for detailed prediction of reactive processes and regulatory applications. Nonetheless, even in such a holistic perspective, the implications for the crop remain out of scope.

LCA represents a different approach to evaluate water reuse where environmental effects are the core of the assessment. It quantifies impacts such as energy demand, greenhouse gas emissions and resource consumption [24] typically framed on the selected treatment technology. Quantitative Microbial Risk Assessment (QMRA) is a key technique targeted at human health implications associated with bacteria and pathogens present in the treated effluent [25]. These two procedures are often combined to provide a comprehensive full evaluation of reuse scenarios [26]. However, despite offering a broad overview of environmental and health dimensions, they overlook the sensitivity and responses of the receiving ecosystems.

A reuse scenario that is technically feasible, economically viable and compliant with water reuse regulations may still exert pressures on the receiving ecosystem. STREAM was developed to explicitly address this decision-making gap.

In contrast with the DSTs presented above, STREAM places the environmental consequences of WWTP effluent reuse on the irrigated crop and the ecological status of the concerned water body at the core of decision-making. While tools such as Poseidon, RWRM and MULTI-ReUse support technology selection and broader sustainability assessments, STREAM presents a dedicated evaluation of environmental compatibility by explicitly considering receiving-water quality and crop suitability within a single framework. Thanks to that, it provides an integrated perspective that complements existing techno-economic and health-oriented DSTs, and helps identify potentially unsuitable reuse scenarios at an early stage of project development.

STREAM is particularly suited to planning and pre-feasibility studies, when decision-makers must compare alternative reuse options using limited site-specific information. However, the framework is not intended to predict pollutant transport and transformation processes, assess temporal variations in water quality, quantify pathogen-related health risks or estimate life-cycle environmental impacts. These aspects remain within the scope of mechanistic models such as WASP, QMRA studies and LCA approaches. Consequently, STREAM should be regarded as a complementary screening tool that helps determine when more detailed analyses are required. It can also be applied to water bodies used for drinking water abstraction. In such cases, STREAM

can support the evaluation of how effluent reuse may influence water availability and water quality in the catchment.

Although developed using datasets and reference values relevant to Luxembourg, the framework is transferable to other geographical contexts because it relies on information commonly available in reuse projects, including effluent quality, crop requirements and receiving-water indicators. Nevertheless, adaptation to local regulations, environmental quality standards and water-body classification systems would also be necessary. Future applications under different climatic, hydrological and regulatory conditions would help further evaluate the robustness and transferability of the framework.

5. Conclusions, Recommendations, and Perspective

The use of treated wastewater for crop irrigation represents a promising strategy to enhance water sustainability by reducing the demand for drinking water and simultaneously recovering nutrients contained in the effluent for agricultural use. The present study illustrates the applicability of STREAM, an open-access DST, for a first assessment of the feasibility and environmental implications of effluent reuse under realistic conditions.

Through the analysis of three case studies, STREAM was able to assess the interactions between hydrological and chemical parameters, and the potential nutrient reuse. Results highlight that both the baseline quality of the receiving water body and the percentage of effluent reuse are important parameters influencing the decision-making. Large WWTPs connected to high-flow rivers may offer the greatest opportunities for sustainable reuse with minimal ecological impact, while smaller facilities in low-flow systems may require stricter hydrological and chemical monitoring.

Overall, STREAM provides a practical screening framework for supporting evidence-based decision-making in planning of WWTP effluent reuse, promoting a circular water economy that aligns environmental protection and agricultural implications.

Although the present study is based on case studies from Luxembourg, the framework can be adapted to other geographical contexts through the adjustment of river typologies, orientation values and crop-specific datasets to reflect local environmental conditions and regulatory requirements.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18141723/s1>, Section Nutrients conversion; Figure S1: View of the Main worksheet, (a) input table to be filled by the user; (b) outputs provided after computations.

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