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Research article

Mathematically formulated key performance indicators for design and evaluation of treatment trains for resource recovery from urban wastewater

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ABSTRACT

While urban wastewater infrastructure is aging and no longer adequate, climate change and sustainability are urging the transition from pollution management to resource recovery. Lacking evidence-based quantitative evaluation of the potential benefits and consequences of resource recovery from wastewater hinders the negotiation amongst stakeholders and slows down the transition. This study proposes mathematical formulations for technical, environmental, economic, and social key performance indicators (KPIs) that can be used to quantify the benefits and the risks of resource recovery. The proposed formulations are derived from the literature and validated with stakeholders. Each KPI is mathematically formulated at treatment train level by considering: (1) the characteristics of individual unit processes (UPs) in the treatment train (TT), (2) the context in which the TT is installed, and (3) the resources to be recovered. The mathematical formulations of the KPIs proposed in this study enable a transparent, consistent and informative evaluation of existing treatment trains, as well as support the (computer aided) design of new ones. This could aid the transition from urban wastewater treatment to resource recovery from urban wastewater.

1. Introduction

A recent evaluation of the European Urban Waste Water Treatment Directive emphasised that compliance with the Directive requires continuous investment to replace or improve inadequate wastewater treatment plants (WWTPs) (European Comission, 2019). The aging of infrastructure is one of the reasons for inadequacy of WWTPs (Corcoran et al., 2010; Marlow et al., 2013). Increasingly stringent regulation due to emerging pollutants and extreme weather conditions due to climate change intensify the inadequacy of conventional WWTPs (Brown et al., 2011; Mo and Zhang, 2013).

Wastewater can be seen as a nuisance but also as a source of reusable and valuable material (Agudelo-Vera et al., 2012; Graaff, 2010; Wielemaker et al., 2018). The recovery of resources from wastewater requires a different approach towards wastewater management and treatment facility design (Diaz-Elsayed et al., 2019; Mehta et al., 2015; Puchongkawarin et al., 2015). An increasing number of technologies capable of recovering resources in different forms (van Eekert et al., 2012; Mehta et al., 2015), together with the demand for renewing aging WWTPs, provides an opportunity to renovate WWTPs towards resource recovery. To design sustainable resource recovery facilities, technical, environmental, economic, and social performance indicators need to be considered in an integrated and comprehensive way (Plakas et al., 2016; Regmi et al., 2019). However, most studies either exclude certain indicators such as social ones (Garrido-Baserba et al., 2015; Puchongkawarin et al., 2015) or focus only on specific ones such as environmental indicators (Fang et al., 2016; Padilla-Rivera and Güereca, 2019; Pasqualino et al., 2010). Furthermore, for consistent decision-making, indicators need to represent measurable or observable quantities (Falck and Spangenberg, 2014). Relevant studies carry out a qualitative analysis which is most of the time subjective (expert-based) or when quantitative analysis is applied, the quantification method is not provided so the quantification is not reproducible. Maybe remove this: Finally, to be practically applicable, indicators should reflect the goals of stakeholders (Mascarenhas et al., 2015; Sterling et al., 2017). However, only a few studies involved stakeholders in selecting indicators for evaluation of

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resource recovery from wastewater (Cornejo et al., 2019; Foxon et al., 2002; Molinos-Senante et al., 2014).

The transition from conventional urban wastewater treatment to resource recovery is slow, mostly because decision-makers are risk-averse and the lack of experience with novel technologies prevents them from implementing resource recovery (Holmgren et al., 2014). A comprehensive quantitative evaluation of treatment facilities can provide a consistent basis for decision-making and thus speed up the implementation of resource recovery from urban wastewater (Regmi et al., 2019). Definitions and quantification of indicators used in literature are often not detailed enough to consistently evaluate technologies or treatment facilities for resource recovery and in most cases not sufficiently complete to conduct an overall integrated assessment (Deng et al., 2013; Muga and Mihelcic, 2008; Shakir et al., 2017). Moreover, studies using various sets of indicators were often engaged in qualitative assessment, based on expert judgment (Kalbar et al., 2012). Such studies do not mention which characteristics are involved and how these contribute to the assessment (Castillo et al., 2016) and therefore lack in offering a rigorous scientific and reproducible approach.

Therefore, this research proposes mathematical formulations for an applicable set of key performance indicators (KPIs) to evaluate treatment facilities that recover resources. Such facilities are referred to as treatment trains (TTs) consisting of interconnected technologies represented as unit processes (UPs). The mathematical formulations are intended to support i) model-based (computer aided) TT design, ii) evaluation of design robustness, and iii) decision-making. The system boundaries applied in this study and the step by step approach for KPI definition and mathematical formulations are presented in Section 2.1 and 2.2, respectively. The definitions and mathematical formulas for each KPI and their validation with the NEREUS Interreg 2 Seas project case studies are provided in Section 3. The study aims to support the delivery of evidence to both private and public decision-makers about the benefits of resource recovery options and help them to mitigate potential risks.

2. Methods

2.1. System boundaries

The recovery of resources from urban wastewater requires one or more interconnected unit processes (UPs) forming treatment trains (TTs) (Fig. 1). A UP is able to treat various types of urban wastewater as well as effluents from other UPs, all varying in quality. In this study, water, total suspended solids (*TSS*), chemical oxygen demand (*COD*), total nitrogen (*TN*) and total phosphorous (*TP*) are used in mass- and flow-balances to quantify the resources recovered (water, energy, nutrients) and evaluate the achieved environmental effluent discharge requirements. Each UP entails a certain capital expenditure and uses consumables during operation and maintenance, such as energy, chemicals, replaced parts, and labour which reflect on operational expenditure. Finally, a TT can recover a single or multiple resources. Thus, a TT can consist of several partial TTs, each individually recovering one particular resource. In case of multiple resources being recovered, the sequence of UPs recovering resource k is considered as a TT on its own (TT_k). For example, in Fig. 1 TT_A includes UP_{X-1}, UP_X and UP_{X+1} for recovering resource A while TT_B includes UP_{X-1} and UP_Y for recovering resource B. This allows mass- and flow-balances per resource recovered and accordingly to quantify KPIs for the whole TT. A UP can serve the recovery of multiple resources (in Fig. 1, UP_{X-1} is used to recover resource A and B), however it needs to be purchased only once.

This study focuses on KPIs that evaluate the technical, social, economic and environmental impacts of all the UPs in the TT but only within the immediate surrounding. The immediate surrounding is considered the area where the wastewater is collected, treated, discharged as well as resources recovered. The time frame considered in this study is limited to purchase and operation of UPs in the TT.

2.2. Defining and formulating KPIs

Various performance indicators are used in the literature on urban wastewater treatment, resource recovery from urban wastewater, and drinking water production. A brief overview of relevant studies and indicators per sustainability category (technical, social, economic and environmental) in the literature are provided in the supplementary material, which shows a diversity of indicators. The most common technical indicators are reliability of effluent quality, flexibility and durability (Supplementary material, Figure S1). Studies accounting for social indicators are mostly using acceptability and public participation (supplementary material, Figure S1). Of the economic indicators, CAPEX, OPEX and net present value (NPV) are the most common ones (Supplementary material, Figure S2). The most chosen environmental indicators are: energy consumption and land requirement (Supplementary material, Figure S2). Only a few studies simultaneously account for all four categories of indicators to evaluate the recovery of water, energy and nutrients (Balkema et al., 2002; Kalbar et al., 2012; Singhirunnusorn and Stenstrom, 2009). Overall the indicators are rarely mathematically formulated (Supplementary material, Table S1).

For sustainability purposes, the NEREUS project stakeholders selected from literature several key performance indicators (KPIs) for each category: technical, economic, environmental and social (Table 1). The stakeholders represented one government/policy-making administrative body from France; three (waste)water companies from Belgium, The Netherlands and United Kingdom; one sustainability services cooperative from Belgium; and three research institutes from Belgium, The Netherlands and United Kingdom.

The KPIs selected by the stakeholders were then mathematically formulated. Mathematical and phrased definitions were searched for in literature. When a KPI had already been mathematically formulated, its

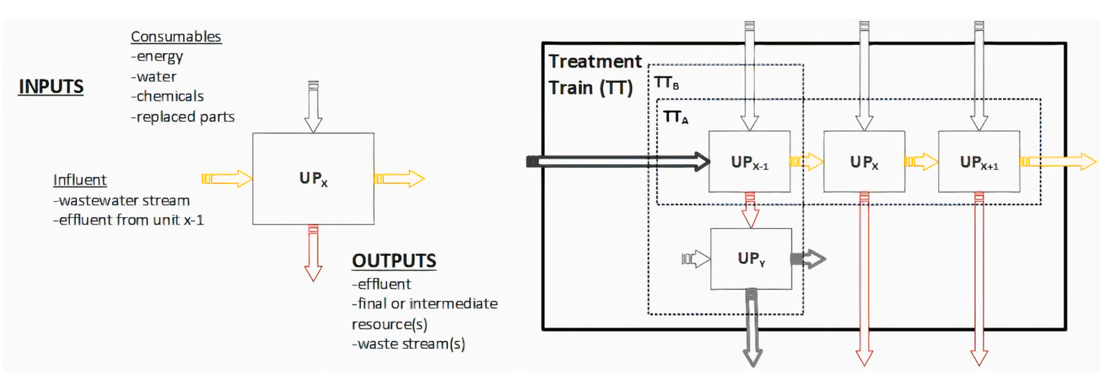

Fig. 1. Left: the generic representation of a unit process (UP) with the main inputs and outputs. Right: the configuration of a treatment train (TT) composed of partial treatment trains per resources (TT_A and TT_B).

Table 1
Key performance indicators (KPIs) selected by the stakeholders per category: technical, environmental, economic and social.

Technical	Environmental	Economic	Social
-Reliability -Flexibility	-Odour -Noise -Footprint -Effluent quality	-CAPEX -OPEX -Willingness to pay for the environment -Potential income generation	-Risk of infections -Risk of toxic components -Affordability -Acceptability

applicability in the given context was checked and further tailored if required. In the absence of a mathematical formulation, a formula for the KPI was generated based on phrased definitions from literature. The applicability of the generated mathematical formulations was checked with the five NEREUS pilot partners. The formulations were refined based on the feedback from each pilot partner. Section 3.1 presents the definitions and mathematical formulations of the KPIs listed in Table 1. The partners were also asked to indicate what characteristics of unit processes (UPs) they could provide and thus be used to quantify the KPIs. The availability of UP characteristics per pilot partner is provided in Section 3.2.

3. Results

3.1. KPI definition and mathematical formulation

3.1.1. Economic

CAPEX and OPEX

Wastewater treatment is known to be costly not only as capital expenditure for purchase, construction, and installation of a TT, but also as operational and maintenance expenditure (Hophmayer-Tokich, 2006). Often capital expenditure (CAPEX) includes land costs (Affleck et al., 2016; Joksimovic, 2007), while operation and maintenance expenditure (OPEX) includes labour costs (Hernández-Chover et al., 2018). In this study the CAPEX and OPEX of the whole TT ($CAPEX_{TT}$, $OPEX_{TT}$) are calculated as shown in equations (1) and (2), respectively.

$$CAPEX_{TT} = \sum_{j \in TT} CAPEX_j \quad (1)$$

$$OPEX_{TT} = \sum_{j \in TT} OPEX_j \quad (2)$$

The CAPEX of a UP in the TT ($CAPEX_j$, euros) represents the one time expenditure for purchasing the UP and the OPEX is the total yearly expenditure for energy, chemicals, replaced components and required labour to operate and maintain a UP ($OPEX_j$, euros/year). When both KPIs are used at the same time, they should be expressed in the same currency.

Potential income generation (PIG)

Resources recovered from wastewater are reused and thus they represent reduction in *OPEX* or a source of income (Diaz-Elsayed et al., 2019; Egle et al., 2016; Mo and Zhang, 2013). In this study, the potential income generation (*PIG*) is expected to depend on the amount of resource recovered (i.e. water, nutrients, and energy) via a TT and the country-specific value of the recovered resource (adapted from Deng et al. (2013)). The resource can be represented by a target component (Khiewwijit et al., 2015). The target components for water, energy and nutrients are water, chemical oxygen demand (*COD*), and total nitrogen (*TN*) and total phosphorous (*TP*), respectively.

$\text{target component} = \{Water, COD, TN, TP\}$

The amount of recovered resources (X_k) is estimated by carrying out the mass-balance of the target component k (equation (3)).

$$X_k = \begin{cases} IC_k * Q_{influent} * \prod_{j \in TT_k} Y_{j,k}, & \forall k \in COD, TN, TP \\ Q_{influent} * \prod_{j \in TT_k} Y_{j,k}, & \forall k \in Water \end{cases} \quad (3)$$

For this, the water and mass flows of the target components need to be calculated considering their recovery or removal percentages ($Y_{j,k}$, equation (4)) by each UP in TT per resource (TT_k).

$$Y_{j,k} = \begin{cases} 1 - R_{j,k} & \text{if after } UP_j \text{ target component k is in main stream} \\ R_{j,k} & \text{if after } UP_j \text{ target component k is in side stream} \end{cases} \quad (4)$$

Considering the values of the recovered resources, all the recovered target components need to be summed to estimate the potential income generation of the whole train (PIG_{TT}) as shown in equation (5).

$$PIG_{TT} = \sum_{k \in \text{target component}} PIG_k \quad (5)$$

where,

$$PIG_k = X_k * H_{TT_k} * D_{TT_k} * VRP_{k,\,c} \quad (6)$$

$\forall c \in country, k \in \text{target component}$

Willingness to pay (WTP)

According to Scheepens et al. (2016), there is a threshold to the number of people willing to pay more for products and services that are associated with environmental benefits. Resource recovery from wastewater could give rise to additional *CAPEX* and *OPEX* thus impose higher wastewater levies on inhabitants or businesses (Mo and Zhang, 2013). The willingness to pay for the additional levies depends on the local economic and environmental context, as well as the costs associated with the implementation and operation of the solution (Rodríguez-Entrena et al., 2012; Zografakis et al., 2010). The proposed mathematical formulation for willingness to pay for environmental benefits for the whole TT (WTP_{TT}) is presented in equation (7).

$$WTP_{TT} = CCA_c * CCT_c * \frac{(NAI_c * PE) + PIG_{TT}}{EAC_{TT}} \quad (7)$$

where,

$$EAC_{TT} = \sum_{j \in TT} EAC_j \quad (8)$$

$$EAC_j = \frac{r(1+r)^{Lt_j}}{(1+r)^{Lt_j} - 1} * \left(CAPEX_j + \sum_{t=1}^{Lt_j} \frac{OPEX_j}{(1+r)^t} \right) \quad (9)$$

Thus, in this study the inhabitantsâ€™ willingness to pay for environmental benefits increases with higher net average income (NAI_c) (Zografakis et al., 2010), climate change awareness (CCA_c), and the number of people by whom climate change (CCT_c) is perceived as a threat (Rodríguez-Entrena et al., 2012). At the same time, the willingness to pay is likely to decrease as the costs for the TT (EAC_{TT}, equation (8)) increase (Zografakis et al., 2010).

3.1.2. Technical KPIs

Reliability

In the context of wastewater treatment, reliability refers to the performance of the TT (e.g. effluent quality) and can depend on the planned and unplanned maintenance activities required between potential downtime events (Eisenberg et al., 2001; Kalbar et al., 2012; Quadros et al., 2010). Often the downtime events are caused by influent quality and quantity fluctuations (Józwiakowski et al., 2017; Sweetapple et al., 2017). Thus, the lifetime, maintenance requirement and influent quality should be accounted for in comprehensive reliability evaluations of UPs. However, in this study, these will be formulated by using other KPIs, namely OPEX and flexibility, respectively.

Since wastewater treatment and resource recovery trains are series of UPs in which the performance of one UP affects the performance of the other UPs, the reliability of a whole TT (Rel_{TT}, equation (10)) is formulated as the product of reliabilities of all UPs (Rel_j, equation (11)) in the whole TT.

$$Rel_{TT} = \prod_{j \in TT} Rel_j \tag{10}$$

This way, the reliability of a UP is proposed to be the likelihood of the UP delivering the expected effluent or recovered resource quality. Usually, this information is provided by technology suppliers in the form of process warranty, which is a function of UP failure rate (fr_j) and for all UPs in the whole TT it should be provided for the same time frame (e.g. per year).

$$Rel_j = 1 - fr_j(p) \tag{11}$$

Flexibility

Conventionally, in the context of (waste)water treatment, flexibility is related to (i) TT performance robustness with changing influent quality and quantity (Kalbar et al., 2012) but also to (ii) modularity which refers to the ease of change in the TT design configuration (Smith, 2009). Since the scope of this study is to define KPIs for evaluating TTs for resource recovery from various urban wastewater streams (e.g. conventional sewage, black water, grey water, etc.), flexibility was limited to explore the optimum operating range of each individual UP (Spiller et al., 2015). Wastewater quality and quantity is typically represented by the common variables that affect the performance of UPs, i.e. concentration of TSS, COD, TN, and TP, temperature, pH and flow. Note, however, that not all UPs are sensitive to each variable. Accordingly, flexibility is estimated by normalising the min-max ranges for the variables ($range_{v,j}$, equation (13)) to which a specific UP is sensitive ($or_{v,j}$, equation (12)).

$$or_{v,j} = \begin{cases} \frac{range_{v,j}}{max_{v,j}} & \text{if } UP_j \text{ is sensitive to variable } v \\ 1 & \text{otherwise} \end{cases} \tag{12}$$

where,

$$range_{v,j} = max_{v,j} - min_{v,j} \tag{13}$$

$$\forall v \in V = \{\text{Flow}, \text{TSS}, \text{COD}, \text{TP}, \text{TN}, \text{Temperature}, \text{pH}\}$$

The final operating range per UP is the average of all normalized min-max ranges.

$$or_j = \sum_{v \in V} or_{v,j} \tag{14}$$

Overall, the greater the normalized min-max range, the higher the flexibility of the UP and eventually of the TT (equation (15)).

$$Flex_{TT} = \frac{\sum_{j \in TT} or_j}{N_{TT}} \tag{15}$$

where, N_{TT} is the number of unit processes in the whole treatment train.

Through this KPI, model-based design and evaluation could explore the applicability of a TT with changing quality and quantity of wastewater streams.

3.1.3. Environmental KPIs

Odour

The potential adverse effects of odours from wastewater treatment facilities on human health and environment is a critical issue that has been studied for decades (Capelli et al., 2011). According to Invernizzi et al. (2016), being exposed to certain odours might impact the human body in the form of anxiety, unease, headache, depression as well as some physical symptoms. Despite the developments for sampling and measuring odour, quantifying the impact of the emitted odour is not an easy task (Lebrero et al., 2011). Odour emissions from wastewater treatment plants differ per process, generally decreasing from primary to tertiary treatment (Muga and Mihelcic, 2008). This can be related to the type of process (OP_j), like biological degradation of the organic matter and the status of the wastewater, like the concentration of pollutants (Gostelow et al., 2001).

$$OP_j = \begin{cases} 1 & \text{if } UP_j \text{ is a physical process} \\ 2 & \text{if } UP_j \text{ is a chemical process} \\ 3 & \text{if } UP_j \text{ is a biological process} \\ 4 & \text{if } UP_j \text{ is a thermal process} \end{cases} \tag{16}$$

The assessment of the odour emission per UP is proposed as the multiplication of the following characteristics: (i) an integer scale which indicates the odour emission potential per type of process (OP_j) and (ii) odour emission per UP (OEP_j, equation (17)) based on the maximum allowed organic matter load expressed as COD concentration ($max_{COD,j}$). If the max COD load is not available for a specific UP then the COD concentration in the UP influent ($Infl_{COD,j}$, equation (18)) should be taken.

$$OEP_j = \begin{cases} max_{COD,j} & \text{if max allowed COD concentration is available for } UP_j \\ Infl_{COD,j} & \text{otherwise} \end{cases} \tag{17}$$

where,

$$Infl_{COD,j} = \frac{IC_{COD} * Q_{influent} * \prod_{1,\dots,j-1} Y_{j-1,COD}}{Q_{influent} * \prod_{1,\dots,j-1} Y_{j,Water}} \tag{18}$$

$$Y_{j,COD} = \begin{cases} 1 - R_{j,COD} & \text{if after } UP_j, \text{ COD is in the main stream} \\ R_{j,COD} & \text{if after } UP_j, \text{ COD is in the side stream} \end{cases} \tag{19}$$

The total odour emission potential of the TT (OEP_{TT}, equation (20)) is estimated by summing the odour emission potentials of each UP in the TT.

$$OEP_{TT} = \sum_{j \in TT} OEP_j * OP_j \tag{20}$$

Noise

Noise constraints for humans differ from those for animals but also per area type and time of the day (WHO, 2018). According to Francis and Barber (2013) continuous noise (pressure) levels of 5–10 dB above ambient levels can affect the abundancy of some bird species. In the case of wastewater treatment plants, UPs can have a specific noise emission potential. Therefore, the levels of noise (dB) emitted by all UPs in the TT are logarithmically influencing the total level of noise (NEP_{TT}) as shown in equation (21) (Berglund et al., 1999).

$$NEP_{TT} = 10 * log10 \sum_{j \in TT} 10^{LNP_j/10} \tag{21}$$

The formulation of this KPI requires the level of noise emitted by each UP (LNP_j) in the train, expressed in dBs. Depending on the type of area in which the TT is located, sound attenuation measures have to be taken to comply with local regulation for noise emission (The European Parliament and the Council of the European Union, 2002).

Footprint

The footprint of a WWTP indicates the surface area used for successfully achieving wastewater discharge requirements. Oertlé et al. (2019) uses "land requirement" as a KPI and takes it into account in decision-making for water recovery from wastewater via a semi-quantitative measurement. According to Tervahauta et al. (2013) the footprint, can differ per UP, but also per type of influent stream from which resources are recovered. In this study, the footprint of a UP is evaluated via the following characteristics: (i) the area in m^2 required per m^3 of influent to be treated (A_j), (ii) the hydraulic retention time (HRT_j), and (iii) the influent flow rate ($Q_{influent}$). The sum of footprints of all UPs in the TT is then used to estimate the footprint of the whole train as presented in equation (22).

$$FP_{TT} = \sum_{j \in TT} A_j * HRT_j * Q_{influent} \tag{22}$$

Effluent quality compliance index (EQCI)

Effluent quality is the main indicator for monitoring the performance of a wastewater treatment plant. Conventionally, wastewater treatment plants are operated such that the final effluent quality complies with local discharge regulations. Effluent discharge regulations differ per country and are stated per pollutant. Pollutant removal efficiencies per UP ($R_{j,i}$) are used to predict final effluent quality by evaluating the achieved final concentration of pollutants in the main stream ($FC_{i,water}$, equation (23)).

$$FC_{i,water} = \frac{IC_i * \prod_{j \in TT_{Water}} (1 - R_{j,i})}{\prod_{j \in TT_{Water}} (1 - R_{j,Water})} \tag{23}$$

where,

$\forall i \in Pollutants = \{TSS, COD, TN, TP\}$

The total removal of each pollutant needs to comply with legal requirements for different discharge locations such as open surface water body, designed surface water body, existing sewer. Depending on the effluent quality standards to be met, a compliance index per TT, in the main stream ($EQCI_{TT}$) is calculated via a pollution index as presented in equation (24).

$$EQCI_{TT} = \begin{cases} 1 & \text{if } PI_{TT_{water}} = 0 \text{ (complying with legislation)} \\ 0 & \text{if } PI_{TT_{water}} \geq 1 \text{(not complying with legislation)} \end{cases} \tag{24}$$

The pollution index ($PI_{TT_{water}}$, equation (25)) is estimated for the main stream (adapted from Shakir et al. (2017)) by summation of the pollution index per pollutant (PI_i, equation (26)).

$$PI_{TT_{water}} = \sum_{i \in Pollutants} PI_i \tag{25}$$

For this, the limit concentrations of pollutants (legal requirements) for different discharge locations ($LC_{i,l,water,c}$) need to be compared with the final concentrations of pollutants in the main stream ($FC_{i,water}$).

$$PI_i = \begin{cases} 1 & \text{if } LC_{i,\ l,\ Water,\ c} < FC_{i,\ Water} \\ 0 & \text{otherwise} \end{cases} \tag{26}$$

where,$i \in$ *Pollutants*, $l \in$ discharge location, $c \in$ countries.

3.1.4. Social KPIs

3.1.4.1. Risk of toxic compounds. Hazard free recovered resources are dependent on the efficiency of TTs in removing potentially toxic compounds present in the original influent such as heavy metals, dyes, other trace organic compounds, etc. (Singh et al., 2018). Similarly to the pollution index proposed by Shakir et al. (2017), this study proposes a ratio ($RatioToxic_{tc,TT_k}$, equation (27)) between the limit concentrations ($LC_{tc,k,c}$) determined by regulations (EPA, 2012; EU Water Directors, 2016; NRMMC et al., 2006; NSW, 2008; The European Parliament and the Council of the European Union, 2019; WHO, 2017) and the predicted final concentration ($FC_{tc,k}$, equation (28)) to evaluate the contamination of recovered resources with any toxic compound.

$$RatioToxic_{tc,TT_k} = \frac{FC_{tc,k}}{LC_{tc,k}} \tag{27}$$

$\forall tc \in$ toxic compound and $\forall k = \{Water, TN, TP\}$

where,

$$FC_{tc,k} = \begin{cases} \dfrac{IC_{tc} * \prod_{j \in TT_k} Y_{j,tc}}{\prod_{j \in TT_k} (Y_{j,Water})} & k : \{TN, TP\} \\ IC_{tc} * \prod_{j \in TT_k} Y_{j,tc} & k : \{Water\} \end{cases} \tag{28}$$

$$Y_{j,tc} = \begin{cases} 1 - R_{j,tc} & \text{if after } UP_j, \text{ toxic compound tc is in main stream} \\ R_{j,tc} & \text{if after } UP_j, \text{ toxic compound tc is in side stream} \end{cases} \tag{29}$$

If any of the toxic compounds in any of the recovered resources in the whole TT exceeds the maximum allowed concentration then there is a risk of contamination with toxic compounds. Otherwise, the higher the $RatioToxic_{tc,TT_k}$ the lower the risk of toxic compounds (RTC_{TT}, equation (30)).

$$RTC_{TT} = \begin{cases} 0 & \text{if any } RatioToxic_{tc,TT_k} \leq 1, \text{ no risk} \\ 1 & \text{if any } RatioToxic_{tc,TT_k} > 1, \text{ potential risk} \end{cases} \tag{30}$$

3.1.4.2. Risk of infection potential. The risk of infection is a great concern when water and nutrients are being recovered from wastewater and reused. The WHO has established a calculation method for this based on the degree of exposure, severity and duration of diseases, as well as the number of people affected (WHO, 2017). This KPI is proposed as a binary indicator to check whether the potential risk of infection is present per resource to be recovered based on the predicted pathogen removal and the removal requirements. The removal of pathogens by UPs is generally expressed in log reductions and the total removal of a specific pathogen (TLR_{i,TT_k}, equation (31)) is the sum of the log reductions of all UPs in the TT.

$$TLR_{i,TT_k} = \sum_{j \in TT_k} LR_{i,j} \forall i \in pathogen \tag{31}$$

where,

$\forall i \in$ pathogen and $\forall k : \{Water, TN, TP\}$

The required pathogen removal is also expressed in log reduction and represents the ratio between the concentration of the pathogen in the influent (IC_i) and the regulatory (health-based) standard per recovered resource ($Cpe_{i,k}$) that could be nationally or internationally valid (EPA, 2012; EU Water Directors, 2016; NRMMC et al., 2006; EPHC et al., 2008; NSW, 2008; WHO, 2017).

$$RLR_{i,k} = log10 \frac{IC_i}{Cpe_{i,k}} \tag{32}$$

Finally the risk of infection potential (ROI_{TT}) is calculated via the ratio between required log reduction ($RLR_{i,k}$, equation (32)) and the total log reduction achieved by a TT per resource (TLR_{i,TT_k}, equation (31)) as shown in equation (33).

$$ROI_{TT} = \begin{cases} 0 & \text{if any } \frac{RLR_{i,k}}{TLR_{i,TT_k}} \leq 1, \text{ no risk} \\ 1 & \text{if any } \frac{RLR_{i,k}}{TLR_{i,TT_k}} > 1, \text{ potential risk} \end{cases} \quad (33)$$

3.1.4.3. Acceptability. This indicator is expected to heavily depend on the need for the recovered resources. Therefore, acceptability of the resources recovered from wastewater by the society might show differences based on the following: (i) the shortage of the product in the country or region (Marks et al., 2008), (ii) degree of human contact, and (iii) potential perceived risks (Nancarrow et al., 2009).

The shortage of the resource is proposed as the demand-supply ratio of this resource per country (Domènech et al., 2010). The degree of human contact (HC_k) depends on the specific use of the resources, such as water for agriculture (NRMMC et al., 2006), food industry (NSW, 2008) or irrigation of parks, and non-edible gardens (Marks et al., 2008).

$$HC_k = \begin{cases} 1 & \text{if k is energy} \\ 2 & \text{if k is nutrients} \\ 3 & \text{if k is irrigation water} \\ 4 & \text{if k is industrial water} \\ 5 & \text{if k is drinking water} \end{cases} \quad (34)$$

The potential perceived risk ($RatioInfection_{TT_k}$, equation (35); $RatioToxic_{TT_k}$, equation (36)) is evaluated via the achieved removal rate of pathogens (TLR_{i,TT_k}) and toxic compounds ($FC_{tc,k}$).

$$RatioInfection_{TT_k} = \sum_{i \in pathogen} \frac{RLR_{i,k}}{TLR_{i,TT_k}} \quad (35)$$

$$RatioToxic_{TT_k} = \sum_{tc \in \text{toxic compounds}} \frac{FC_{tc,k}}{LC_{tc,k}} \quad (36)$$

The KPI formulation as proposed in this study (equation (37)) shows that the higher the demand-supply ratio ($DS_{k,c}$) and the lower the degree of human contact (HC_k) with resource in consideration, the more acceptable a TT is.

$$Acceptability_{TT} = \sum_k \frac{DS_{k,c}}{RatioInfection_{TT_k} * RatioToxic_{TT_k} * HC_k} \quad (37)$$

where,

$k \in \text{recovered resources}, c = country$

3.1.4.4. Affordability. Affordability is intrinsically context dependent (Muga and Mihelcic, 2008) and generally considered to be an economic indicator (Bozileva et al., 2018). For example, in low-income countries affordability and simplicity play an important role while in high-income countries, sustainability is one of the most commonly used and aimed for concepts (Mara, 2004). In this study affordability is considered to be a social KPI, indicating the purchasing power of a community. The mathematical formulation proposed for this KPIs is provided in equation (38).

$$Affordability_{TT} = \frac{(PE * NAI_c) + PIG_{TT}}{EAC_{TT}} \quad (38)$$

with this method it is assumed that the higher the population size served by the TT and the net average income, the more affordable a TT becomes. The characteristics that are expected to negatively affect affordability are equivalent annual costs (EAC_{TT}, equation (8)), as these would increase the levies that the population served has to pay. The affordability would however increase when capital income is expected from the sales of the recovered resources (PIG_{TT}, equation (5)).

3.2. Case studies

The applicability check revealed that a few UP characteristics are not available for all the UPs tested by the NEREUS pilot partners (Table 2). For example, the level of noise emission per UP is not readily available. Unless the UP suppliers can provide this information or the noise levels are measured, it will not be possible to quantify this environmental KPI as proposed in this study. Similarly, the removal percentage of certain toxic compounds as well as the removal of specific pathogens are not available for all UPs. Therefore, the risk of toxic compounds and the risk of infection cannot be calculated. The calculation of these two KPIs can also be affected by the inconsistency between the available data on removal percentages of specific compounds and the limit concentrations for these compounds. For example, there is a limit concentration for E. coli in fertilizing products (The European Parliament and the Council of the European Union 2019). The removal percentages of this pathogen are known for some UPs such as anaerobic digestion but they are neither known nor measured for other UPs such as sieves and electro-coagulation. Moreover, the concentrations of specific toxic compounds and pathogens in the influent should be provided as well to determine their fate in the treatment train. At the time of the validation, only pilot partner 1 and 4 could provide influent concentrations for a chosen heavy metal (i.e. Pb), while none of the partners could provide the influent concentrations of pathogens (i.e. *E. coli*).

4. Discussion

This study proposes an applicable set of KPIs, including their definition and mathematical formulation for the design and evaluation of treatment trains (TTs) for resource recovery. Each KPI is mathematically formulated by considering the characteristics of (i) individual unit processes (UPs), (ii) the context in which they are installed, and (iii) the resources to be recovered. This study succeeded in mathematically formulating the KPIs such that they can be applied for any TT, context, and resource(s) to be recovered.

While mathematically formulating KPIs, in this study two categories were observed: (i) constraints (go/no go) and (ii) evaluation indicators. The first category, constraints are indicators that use legislative or regulative characteristics in their definition. These set the limitations to which a TT is environmentally and socially viable (Holmgren et al., 2014) and thus which TT may be considered for further evaluation. From – 1 the following KPIs are constraints: effluent quality (EQCI, equation (24)), risk of toxic compounds (RTC, equation (30)), risk of infections (ROI, equation (33)).

Overall, resource recovery and reuse related risks can be of various

Table 2
Applicability check with pilot partners (PP) of the NEREUS project. + means that data per characteristic needed to calculate the specific KPI is fully available; +/− means that data per characteristic needed to calculate the specific KPI is not available for all UPs in the TT; - means that data per characteristic needed to calculate the specific KPI is not available for any of the UPs in the TT.

KPI		PP 1	PP 2	PP 3	PP 4	PP 5
Economic	CAPEX	+	+	+	+	+
	OPEX	+	+	+	+	+
	PIG	+	+	+	+	+
	WTP	+	+	+	+	+
Technical	Reliability	+	+	+	+	+
	Flexibility	+	+	+	+	+
Environmental	Odour	+	+	+	+	+
	Noise	+/−	+/−	+/−	+/−	+/−
	Footprint	+	+	+	+	+
	EQCI	+	+	+	+	+
Social	RTC	−	+	−	+	−
	ROI	−	−	−	−	−
	Acceptability	+	+	+	+	+
	Affordability	+	+	+	+	+

kinds including human health, environment, management, and financial. Risk of infection and risk of toxic compounds are the two most important risks related to the reuse of recovered resources (Holmgren et al., 2014), addressing human health and safety. Affordability, acceptability, willingness to pay (WTP) and the potential income generation (PIG) are other KPIs proposed in this study that could be used to evaluate financial and management related risks.

During the definition and formulation process, overlaps between KPIs were acknowledged. The value tree approach (Fig. 2) was used to visualize the overlaps of the UP characteristics used in the formulation of each KPI (Angelis and Kanavos, 2017). Some UP characteristics were used in the formulation of more than one KPI. Accordingly, the more often a characteristic is used the higher the importance of that characteristic in the final evaluation. Furthermore, it can be observed that eventually all categories of KPIs make use of removal/recovery percentages of effluent quality parameters, showing that the same parameters are used to evaluate seemingly different aspects. While acceptability and affordability could be evaluated via social inquiries, in this study the evaluation was broken down to UP level to differentiate quantitatively between treatment alternatives.

Several KPIs were defined by using other KPIs considered in this study. For example, affordability and willingness to pay (WTP) were formulated with the help of the following economic KPIs: CAPEX, OPEX and potential income generation (PIG). Since the recovery/removal percentages of UPs are needed to calculate the PIG, these UP characteristics are eventually used in the formulation of PIG, affordability, and WTP. While the mathematical formulas of these three KPIs clearly overlap, their meaning is essentially different. Each individual KPI has its own meaning and thus should be considered for TT evaluation and design purposes.

The validation of the mathematical formulations revealed that the quantification of KPIs can be affected by the lack of data per UP. The lack of data per UP can be explained in two ways: (i) the data is not needed or considered irrelevant or (ii) the data is not available. This leaves two options to the end-user or decision-maker: (i) the KPI is considered irrelevant or (ii) the KPI is important and data should be collected for current and future use.

By providing a clear definition with mathematical formulation for KPIs, this study creates a transparent interface whereby the decision-maker or end-user gains insight into the content of each KPI. Firstly, the KPIs can be used to evaluate the contribution of individual UPs and accordingly to assess the impact of replacing technology for adaptation of the treatment facility towards future needs. Secondly, the KPIs can be used to evaluate the robustness of a planned design when for example influent characteristics and product quality requirements change. Thirdly, the KPIs allow the user to study trade-offs between various technologies and assign weights to show the importance of each KPI, resulting in balanced and consistent decision or design evaluation. Uncertainties related to the mathematical formulations of the KPIs will be incorporated into a future study by means of sensitivity analysis.

Future work will focus on wider environmental impact analysis via Life Cycle Assessment (LCA) methods (Cornejo et al., 2019; Mihelcic et al., 2017). The mathematical formulations of KPIs and LCA based indicators will be integrated in a decision-making framework. The framework will be meant to find the most appropriate approaches, including extensions of current wastewater treatment plants and new designs, and the optimum scales for recovering various resources from urban wastewater. The follow-up studies will also further help validating the mathematical formulations proposed in this study.

5. Conclusions

Mathematically formulating a set of sustainability KPIs as proposed in this study enables a transparent and consistent evaluation of existing TTs and supports the (computer aided) design of new solutions. The KPIs provide insight into the selection of alternative technologies and trade-offs during design and decision-making, and they indicate to what extent certain social, technical, environmental and economic aspects influence the evaluation of a treatment facility. For design purposes social and environmental constraints are critical, since they ensure viability of the TT. Mathematically formulating these constraints contributes to understanding the importance of aligning information from technology suppliers with local, national or international regulation.

Credit author statement

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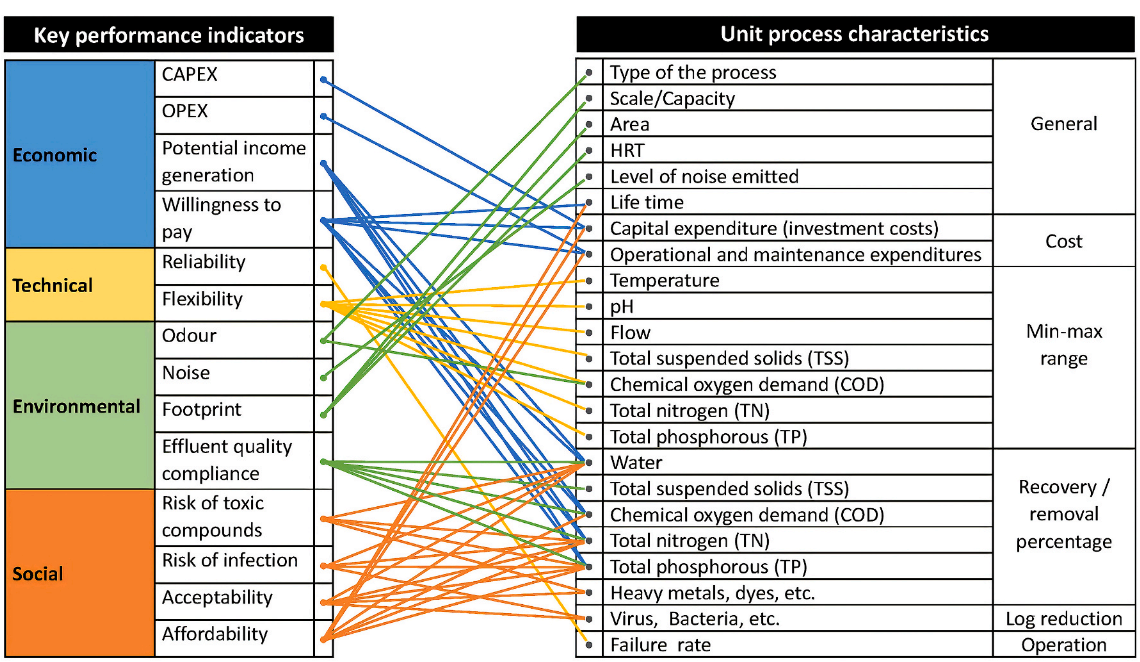

Fig. 2. Unit process characteristics (right) used in the mathematical formulation of key performance indicators (left).

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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.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2020.111916.

Abbreviations	Unit	Description
UP	–	Unit Process
TT	–	Treatment train
TT_k	–	Treatment train involved in recovering compound k
A_j	m^2/m^3	Surface area required for *UP* j
$Acceptability_{TT}$	–	Acceptability of the whole *TT*
$Affordability_{TT}$	–	Affordability of the whole *TT*
$CAPEX_j$	€	Capital expenditure of the *UP* j
$CAPEX_{TT}$	€	Total capital expenditure for whole *TT*
CCA_c	%	Percentage of people aware of climate change per country c
CCT_c	%	Percentage of people perceiving climate change as a threat per country c
$Cpe_{i,k}$	cfu/100 ml	Limit concentration of pathogen i equivalent to 10^{-6} DALYS pppy for resource k
D_{TT}	days	Number of days of operation of *TT*
$DS_{k,c}$	–	Demand supply ratio of resource k in country c
EAC_j	€/year	Equivalent annual cost for *UP* j
EAC_{TT}	€/year	Equivalent annual cost for the whole *TT*
$EQCI_{TT}$	binary (0–1)	Effluent quality compliance index for the whole *TT*
FC_{ik}	mg/L	Final concentration of compound i in recovered resource k
$Flex_{TT}$	–	Flexibility of the whole *TT*
FP_{TT}	m^2	Land footprint of the whole *TT*
$fr_j(p)$	%	Failure rate of *UP* j in specific time period
H_{TT}	hours	Number of hours of operation per day for the *TT*
HC_k	Scale 1-5	Degree of human contact per recovered resource k
HRT_j	hours	Hydraulic retention time per *UP* j
IC_i	mg/l	Initial concentration of compound i in the influent of the *TT*
$Infl_{COD,j}$	mg/l	Concentration of the COD in the influent of the *UP* j
$LC_{i,l,k,c}$	mg/l	Limit concentration for compound i per location l per resource k per country c
LNP_j	dB	Level of noise potential per unit process in dB
$LR_{i,j}$	log scale	Log reduction of compound i by unit process j
Lt_j	years	Life time per *UP* j
$max_{v,j}; min_{v,j}$	–	Minimum required and maximum allowed value for the variable v per *UP* j
NAI_c	€/pppy	Net average income per person per year in country c
NEP_{TT}	dB	Noise emission potential by the whole *TT*
OEP_j	–	Odour emission potential by unit process j
OEP_{TT}	–	Odour emission potential by the whole *TT*
OP_j	scale 1-4	Odour potential per type of process
$OPEX_j$	€/year	Operational expenditure of the *UP* j
$OPEX_{TT}$	€/year	Total operational expenditure for whole *TT*
$or_{v,j}$	–	Operating range for variable v of *UP* j
PE	people	Population equivalent
PI_i	binary (0–1)	Pollution index for compound i
PI_{TT_k}	–	Total pollution index of *TT* for recovered resource k
PIG_k	€/year	Potential income generated by the recovery resource k
PIG_{TT}	€/year	Potential income generated by the whole *TT*
Pppy	–	per person per year
$Q_{influent}$	m^3/hour	*TT* influent flow rate
R	%	Yearly discount rate (depreciation rate)
$R_{j,k}$	%	Percentage of compound k that goes to the side stream in *UP* j
$range_{v,j}$	–	Operating range per variable v of *UP* j
$RatioInfection_{TT_k}$	–	Perceived potential risk of contamination with pathogens
$RatioToxic_{TT_k}$	–	Perceived potential risk of contamination with toxic compounds

(continued on next page)

(*continued*)

Rel_{TT}	%	Reliability of the whole *TT*
RI_{TT}	binary (0–1)	Risk of infection for the whole *TT*
$RLR_{i,k}$	log scale	Required log reduction of pathogen i per recovered resource k
RTC_{TT}	binary (0–1)	Risk of toxic compound for the whole *TT*
TLR_{i,TT_k}	log scale	Total log reduction of pathogen i achieved via *TT* for the resource k
$VRP_{k,c}$	€/m^3, €/kg	Value of the recovered resource k in country c
WTP_{TT}	–	Willingness to pay for the environment for whole *TT*
X_k	kg/hr, m^3/hr	The (mass) flow rate of recovered resource k
$Y_{j,k}$	%	Removal/recovery % of compound k by *UP* j, for the main/side stream

References

Affleck, M., Allen, G., Bozalongo, C.B., Brown, H., Gasson, C., Gasson, J., González-Manchón, C., Hudecova, M., McFie, A., Shuttleworth, H., Tan, M., Underwood, B., Uzelac, J., Virgili, F., Walker, C., 2016. Water ' S digital future.

Agudelo-Vera, C.M., Leduc, W.R., Mels, A.R., Rijnaarts, H.H., 2012. Harvesting urban resources towards more resilient cities. Resour. Conserv. Recycl. 64, 3–12. https://doi.org/10.1016/j.resconrec.2012.01.014.

Angelis, A., Kanavos, P., 2017. Multiple criteria decision analysis (MCDA) for evaluating new medicines in health technology assessment and beyond: the advance value framework. Soc. Sci. Med. 188, 137–156. https://doi.org/10.1016/j.socscimed.2017.06.024.

Balkema, A.J., Preisig, H.A., Otterpohl, R., Lambert, F.J., 2002. Indicators for the sustainability assessment of wastewater treatment systems. Urban Water 4, 153–161. https://doi.org/10.1016/S1462-0758(02)00014-6.

Berglund, B., Lindvall, T., Schwela, D.H., 1999. Guidelines for community noise. Technical Report.

Bozileva, E., Leusbrock, I., Cappon, H.J., Rijnaarts, H.H., Keesman, K.J., 2018. How to analyse urban resource cycles: a dynamic systems approach to facilitate decision-making. IFAC-PapersOnLine 51, 541–546. https://doi.org/10.1016/j.ifacol.2018.03.091. URL:

Brown, R., Ashley, R., Farrelly, M., 2011. Political and professional agency entrapment: an agenda for urban water research. Water Resour. Manag. 4037–4050. https://doi.org/10.1007/s11269-011-9886-y.

Capelli, L., Sironi, S., Del Rosso, R., Céntola, P., Rossi, A., Austeri, C., 2011. Odour impact assessment in urban areas : case study of the city of Terni. Procedia Environmental Sciences 13725. https://doi.org/10.1016/j.proenv.2011.03.018.

Castillo, A., Porro, J., Garrido-Baserba, M., Rosso, D., Renzi, D., Fatone, F., Gómez, V., Comas, J., Poch, M., 2016. Validation of a decision support tool for wastewater treatment selection. J. Environ. Manag. 184, 409–418. https://doi.org/10.1016/j.jenvman.2016.09.087.

Corcoran, E., Nellemann, C., Baker, E., Bos, R., Osborn, D., Savelli, H., 2010. SICK water? The central role OF wastewater management IN sustainable development. A rapid response assessment. Technical Report.

Cornejo, P.K., Becker, J., Pagilla, K., Mo, W., Zhang, Q., Mihelcic, J.R., Chandran, K., Sturm, B., Yeh, D., Rosso, D., 2019. Sustainability metrics for assessing water resource recovery facilities of the future. Water Environ. Res. 91, 45–53. https://doi.org/10.2175/106143017X15131012187980.

Deng, Y., Cardin, M.A., Babovic, V., Santhanakrishnan, D., Schmitter, P., Meshgi, A., 2013. Valuing flexibilities in the design of urban water management systems. Water Res. 47, 7162–7174. https://doi.org/10.1016/j.watres.2013.09.064.

Diaz-Elsayed, N., Rezaei, N., Guo, T., Mohebbi, S., Zhang, Q., 2019. Wastewater-based resource recovery technologies across scale: a review. Resour. Conserv. Recycl. 145, 94–112. https://doi.org/10.1016/j.resconrec.2018.12.035.

Domènech, L., March, H., Saurí, D., 2010. Degrowth initiatives in the urban water sector ? A social multi-criteria evaluation of non-conventional water alternatives in Metropolitan Barcelona. J. Clean. Prod. 38, 44–55. https://doi.org/10.1016/j.jclepro.2011.09.020.

van Eekert, M., Weijma, J., Verdoes, N., De Buisonjé, F., Reitsma, B., Van den Bulk, J., Van Gastel, J., 2012. Explorative research on innovative nitrogen recovery. Technical Report. STOWA. URL: https://www.stowa.nl/publicaties/explorative-research-innovative-nitrogen-recovery.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: an integrated comparative technological, environmental and economic assessment of P recovery technologies. Sci. Total Environ. 571, 522–542. https://doi.org/10.1016/j.scitotenv.2016.07.019.

Eisenberg, D., Soller, J., Sakaji, R., Olivieri, A., 2001. A methodology to evaluate water and wastewater treatment plant reliability. Water Sci. Technol. 43, 91–99.

EPA, 2012. Guidelines for Water Reuse. Technical Report. EPA.

EPHC, NHMRC, NRMMC, 2008. Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2). Augmentation of Drinking Water Supplies. Technical Report. Environment Protection and Heritage Council, National Health and Medical Research Council, Natural Resource Management Ministerial Council.

EU Water Directors, 2016. Guidelines on Integrating Water Reuse into Water Planning and Management in the Context of the WFD. Technical Report, European Commission.

European Comission, 2019. Evaluation of the urban WasteWater treatment directive. Technical Report.

Falck, W.E., Spangenberg, J.H., 2014. Selection of social demand-based indicators : EO-based indicators for mining. J. Clean. Prod. 84, 193–203. https://doi.org/10.1016/j.jclepro.2014.02.021.

Fang, L.L., Valverde-Pérez, B., Damgaard, A., Plósz, B.G., Rygaard, M., 2016. Life cycle assessment as development and decision support tool for wastewater resource recovery technology. Water Res. 88, 538–549. https://doi.org/10.1016/j.watres.2015.10.016.

Foxon, T.J., Gilmour, D., Souter, N., Ashley, R., Butler, D., Pearson, P., Jowitt, P., Moir, J., 2002. Sustainability criteria for decision support in the UK water industry. J. Environ. Plann. Manag. 45, 285–301. https://doi.org/10.1080/0964056022011634.

Francis, C.D., Barber, J.R., 2013. A framework for understanding noise impacts on wildlife: an urgent conservation priority. Front. Ecol. Environ. 11, 305–313. URL: http://www.jstor.org/stable/23470482.

Garrido-Baserba, M., Molinos-Senante, M., Abelleira-Pereira, J.M., Fdez-Güelfo, L.A., Poch, M., Hernández-Sancho, F., 2015. Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems. J. Clean. Prod. 107, 410–419. https://doi.org/10.1016/j.jclepro.2014.11.021.

Gostelow, P., Parsons, S., Stuetz, R., 2001. Odour measurements for sewage treatment works. Water Res. 35, 579–597. https://doi.org/10.1016/S0043-1354(00)00313-4.

Graaff, M.S.D., 2010. Resource Recovery from Black Water. Ph.D. thesis. Wageningen University. URL: https://edepot.wur.nl/134979.

Hernández-Chover, V., Bellver-Domingo, Á., Hernández-Sancho, F., 2018. Efficiency of wastewater treatment facilities: the influence of scale economies. J. Environ. Manag. 228, 77–84. https://doi.org/10.1016/j.jenvman.2018.09.014.

Holmgren, K.E., Li, H., Verstraete, W., Cornel, P., 2014. State of the art compendium report on resource recovery from water. Technical Report. URL: https://iwa-network.org/publications/state-of-the-art-compendium-report-on-resource-recovery-from-water/.

Hophmayer-Tokich, S., 2006. In: Wastewater Management Strategy: Centralized versus Decentralized Technologies for Small Communities, vol. 271. Center for Clean Technology and Environmental Policy, p. 27. URL: https://research.utwente.nl/en/publications/wastewater-management-strategy-centralized-v-decentralized-techno.

Invernizzi, M., Capelli, L., Sironi, S., 2016. Quantification of odour annoyance-nuisance. Chemical Engineering Transactions 54, 205–210. https://doi.org/10.3303/CET1654035.

Joksimovic, D., 2007. Decision Support System for Planning of Integrated Water Reuse Projects. Ph.D. thesis. University of Exeter. URL: https://ore.exeter.ac.uk/repository/handle/10036/28632.

Józwiakowski, K., Bugajski, P., Mucha, Z., Wójcik, W., Jucherski, A., Nastawny, M., Siwiec, T., Mazur, A., Obros, R., 2017. Reliability and efficiency of pollution removal during long-term operation of a one-stage constructed wetland system with horizontal flow. Separ. Purif. Technol. 187, 60–66. https://doi.org/10.1016/j.seppur.2017.06.043.

Kalbar, P.P., Karmakar, S., Asolekar, S.R., 2012. Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. J. Environ. Manag. 113, 158–169. https://doi.org/10.1016/j.jenvman.2012.08.025.

Khiewwijit, R., Temmink, H., Rijnaarts, H., Keesman, K.J., 2015. Energy and nutrient recovery for municipal wastewater treatment: how to design a feasible plant layout? Environ. Model. Software 68, 156–165. https://doi.org/10.1016/j.envsoft.2015.02.011.

Lebrero, R., Bouchy, L., Stuetz, R., Muñoz, R., Lebrero, R., Bouchy, L., Stuetz, R., 2011. Odor assessment and management in wastewater treatment plants : a review. Environ. Sci. Technol. 3389 https://doi.org/10.1080/10643380903300000.

Mara, D.D., 2004. Domestic Wastewater Treatment in Developing Countries. Routledge.

Marks, J., Martin, B., Zadoroznyj, M., 2008. How Australians order acceptance of recycled water National baseline data. J. Sociol. 44, 83–99. https://doi.org/10.1177/1440783307085844.

Marlow, D.R., Moglia, M., Cook, S., Beale, D.J., 2013. Towards sustainable urban water management: a critical reassessment. Water Res. 47, 7150–7161. https://doi.org/10.1016/j.watres.2013.07.046.

Mascarenhas, A., Nunes, L.M., Ramos, T.B., 2015. Selection of sustainability indicators for planning: combining stakeholders' participation and data reduction techniques. J. Clean. Prod. 92, 295–307. https://doi.org/10.1016/j.jclepro.2015.01.005.

Mehta, C.M., Khunjar, W.O., Nguyen, V., Tait, S., Batstone, D.J., 2015. Technologies to recover nutrients from waste streams: a critical review. Crit. Rev. Environ. Sci. Technol. 45, 385–427. https://doi.org/10.1080/10643389.2013.866621.

Mihelcic, J.R., Ren, Z.J., Cornejo, P.K., Fisher, A., Simon, A.J., Snyder, S.W., Zhang, Q., Rosso, D., Huggins, T.M., Cooper, W., Moeller, J., Rose, B., Schottel, B.L.,

Turgeon, J., 2017. Accelerating innovation that enhances resource recovery in the wastewater sector: advancing a national testbed network. Environ. Sci. Technol. 7749–7758. https://doi.org/10.1021/acs.est.6b05917 doi.
Mo, W., Zhang, Q., 2013. Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants. J. Environ. Manag. 127, 255–267. https://doi.org/10.1016/j.jenvman.2013.05.007.
Molinos-Senante, M., Gómez, T., Garrido-baserba, M., 2014. Assessing the sustainability of small wastewater treatment systems : a composite indicator approach. Sci. Total Environ. 497, 607–617. https://doi.org/10.1016/j.scitotenv.2014.08.026.
Muga, H.E., Mihelcic, J.R., 2008. Sustainability of wastewater treatment technologies. J. Environ. Manag. 88, 437–447. https://doi.org/10.1016/j.jenvman.2007.03.008.
Nancarrow, B.E., Leviston, Z., Tucker, I.D., 2009. Measuring the predictors of communities ' behavioural decisions for potable reuse of wastewater decisions for potable reuse of wastewater. Water Sci. Technol. 60 (12), 3199–3209. https://doi.org/10.2166/wst.2009.759.
Nrmmc, Ephc, A.H.M.C., 2006. Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1). Natural Resource Management Ministerial Council, Environment Protection and Heritage Council and Australian Health Ministers Conference.
NSW, 2008. Water reuse guideline for food businesses in NSW considering reusing water. Technical Report May.
Oertlé, E., Hugi, C., Wintgens, T., Karavitis, C.A., 2019. Poseidonâ€"decision support tool for water reuse. Water 11, 153. https://doi.org/10.3390/w11010153.
Padilla-Rivera, A., Güereca, L.P., 2019. A proposal metric for sustainability evaluations of wastewater treatment systems (SEWATS). Ecol. Indicat. 103, 22–33. https://doi.org/10.1016/j.ecolind.2019.03.049.
Pasqualino, J.C., Meneses, M., Castells, F., 2010. Life cycle assessment of urban wastewater reclamation and reuse alternatives. J. Ind. Ecol. 15, 49–63. https://doi.org/10.1111/j.1530-9290.2010.00293.x.
Plakas, K.V., Georgiadis, A.A., Karabelas, A.J., 2016. Sustainability Assessment of Tertiary Wastewater Treatment Technologies: A Multi-Criteria Analysis, vol. 73. IWA Publishing Water Science & Technology, pp. 1532–1540. https://doi.org/10.2166/wst.2015.630.
Puchongkawarin, C., Gomez-Mont, C., Stuckey, D.C., Chachuat, B., 2015. Optimization-based methodology for the development of wastewater facilities for energy and nutrient recovery. Chemosphere 140, 150–158. https://doi.org/10.1016/j.chemosphere.2014.08.061.
Quadros, S., João Rosa, M., Alegre, H., Silva, C., 2010. A performance indicators system for urban wastewater treatment plants. Water Sci. Technol. 62, 2398–2407. https://doi.org/10.2166/wst.2010.526.
Regmi, P., Stewart, H., Amerlinck, Y., Arnell, M., García, P.J., Johnson, B., Maere, T., Miletić, I., Miller, M., Rieger, L., et al., 2019. The future of wrrf modelling–outlook and challenges. Water Sci. Technol. 79, 3–14. https://doi.org/10.2166/wst.2018.498.
Rodríguez-Entrena, M., Barreiro-hurlé, J., Gómez-limón, J.A., Espinosa-goded, M., 2012. Evaluating the demand for carbon sequestration in olive grove soils as a strategy toward mitigating climate change. J. Environ. Manag. 112, 368–376. https://doi.org/10.1016/j.jenvman.2012.08.004.
Scheepens, A.E., Vogtländer, J.G., Brezet, J.C., 2016. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. J. Clean. Prod. 114, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075.
Shakir, E., Zahraw, Z., Al-Obaidy, A.H.M., 2017. Environmental and health risks associated with reuse of wastewater for irrigation. Egyptian Journal of Petroleum 26, 95–102. https://doi.org/10.1016/j.ejpe.2016.01.003.
Singh, N.B., Nagpal, G., Agrawal, S., Rachna, 2018. Water purification by using adsorbents: a review. Environmental Technology & Innovation 11, 187–240. https://doi.org/10.1016/j.eti.2018.05.006.
Singhirunnusorn, W., Stenstrom, M., 2009. Appropriate wastewater treatment systems for developing countries: criteria and indictor assessment in Thailand. Water Sci. Technol. 59, 1873–1884. https://doi.org/10.2166/wst.2009.215.
Smith, B., 2009. Re-thinking wastewater landscapes: combining innovative strategies to address tomorrow's urban wastewater treatment challenges. Water Sci. Technol. 60, 1465–1473. https://doi.org/10.2166/wst.2009.473.
Spiller, M., Vreeburg, J.H.G., Leusbrock, I., Zeeman, G., 2015. Flexible design in water and wastewater engineering e De fi nitions , literature and decision guide. J. Environ. Manag. 149, 271–281. https://doi.org/10.1016/j.jenvman.2014.09.031.
Sterling, E.J., Betley, E., Sigouin, A., Gomez, A., Toomey, A., Cullman, G., Malone, C., Pekor, A., Arengo, F., Blair, M., Filardi, C., Landrigan, K., Luz, A., 2017. Assessing the evidence for stakeholder engagement in biodiversity conservation. Biol. Conserv. 209, 159–171. https://doi.org/10.1016/j.biocon.2017.02.008.
Sweetapple, C., Fu, G., Butler, D., 2017. Reliable, robust, and resilient system design framework with application to wastewater-treatment plant control. J. Environ. Eng. 143, 04016086 https://doi.org/10.1061/(ASCE)EE.1943-7870.0001171.
Tervahauta, T., Hoang, T., Hernández, L., Zeeman, G., Buisman, C., 2013. Prospects of source-separation-based sanitation concepts: a model-based study. Water 5, 1006–1035. https://doi.org/10.3390/w5031006.
The European Parliament and the Council of the European Union, 2002. DIRECTIVE 2002/49/EC of the EUROPEAN PARLIAMENT and of the COUNCIL of 25 June 2002 Relating to the Assessment and Management of Environmental Noise. The European Parliament and the Council of the European Union.
The European Parliament and the Council of the European Union, 2019. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and Repealing Regulation. The European Parliament, The Council of the European Union.
WHO, 2017. POTABLE REUSE. Guidance for producing safe drinking-water. Technical Report.
WHO, 2018. Environmental noise guidelines for the European region. Technical Report.
Wielemaker, R.C., Weijma, J., Zeeman, G., 2018. Harvest to harvest: recovering nutrients with new sanitation systems for reuse in urban agriculture. Resour. Conserv. Recycl. 128, 426–437. https://doi.org/10.1016/j.resconrec.2016.09.015.
Zografakis, N., Sifaki, E., Pagalou, M., Nikitaki, G., Psarakis, V., Tsagarakis, K.P., 2010. Assessment of public acceptance and willingness to pay for renewable energy sources in crete. Renew. Sustain. Energy Rev. 14, 1088–1095. https://doi.org/10.1016/j.rser.2009.11.009.