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# Environmental assessment of municipal wastewater discharges: a comparative study of evaluation methods

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**Abstract**
*Purpose* Wastewater treatment plants produce high environmental impacts on receiving water bodies and pose economic burdens on municipalities or industrial facilities. Their overall operational costs and achieved effluent quality depend very much on the influent type, presence of priority pollutants, treatment technology and required effluent quality (for discharge or for recycle/reuse). Life cycle assessment (LCA), environmental impact quantification (EIQ) and water footprint (WF) are important instruments for sustainability assessments applied for products, production and consumption evaluations in connection with natural resources depletion and pollution threats. This study focuses on the environmental assessment of a municipal wastewater treatment plant (MWWTP) discharges by means of these three evaluation methods with the purpose to understand their (methodological) weak and strong points in capturing the impacts. Such a comparative analysis is necessary to understand how the (individual) advantages provided by each of these instruments can be complimentarily used to improve an assessment framework for various stakeholders concerned with water use cycle management (regional water operators, water management authority, public authorities, research entities, societal organizations, etc.).
*Methods* The three assessment methodologies (LCA, EIQ, WF) are presented, implemented and critically analysed based on a unitary set of data concerning the MWWTP of Iasi city (a municipality of approx. 300,000 inhabitants situated in the North Eastern region of Romania), the wastewater and river water quality indicators as well as all the other relevant data being collected for the year 2012.
*Results and discussion* Although the three methodologies have different principles for environmental impact quantification, the results have shown that most impacts induced to surface waters due to Iasi MWWTP effluents are given by the nutrients (nitrogen and phosphorous compounds), which could induce an eutrophication impact, and to a lesser extent by pollutants responsible for toxicity impacts (such as heavy metals).
*Conclusions* Based on the results of this comparative study, a critical analysis of these three methods was realized by considering the data requirements, their development and integration status. Furthermore, the strong and weak points that are relevant for each method implementation and their subsequent use by decision-makers and Water Authorities are discussed, in the context of legislative requirements (including the Water Framework Directive), actual development of regional water operators and stakeholders' interests.

**Keywords** Environmental impact quantification · Life cycle assessment · (Grey) water footprint · Municipal wastewater treatment plant

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## 1 Introduction

Water is one of the most precious natural resources which has been the subject of ever increasing environmental impacts, as a consequence of its continuous exploitation for meeting the human needs for economic and social development and those due to climate change. Rivers are exposed to severe problems due to multiple uses such as drinking/industrial water, food, hydropower, navigation, irrigation and recreation, etc., being also the place to discharge municipal/industrial wastewaters with various degrees of treatment. The *Integrated Water Resources Management* concept implementation and the achievement of the objectives of the Water Framework Directive (WFD) raise high challenges for the EU member states, which have to solve in an integrated way the issues related to the *water use cycle* (i.e. water supply, industrial and municipal use, wastewater treatment and recycling) (Lemos et al. 2013; Teodosiu et al. 2012; Teodosiu et al. 2013). The most important WFD objective requires that, by 2015, all water bodies within Europe achieve a *good status* which is defined for each type of water resources based on a set of physical–chemical and ecological characteristics (EC 2000).

Wastewater treatments plants (WWTPs) produce high impacts on the receiving water bodies, both environmental and economic, but it is also true that these impacts would be much higher in their absence. Their overall costs and achieved effluent quality depend very much on the influent type and presence of priority pollutants, treatment technology and required effluent quality (for discharge or for recycle/reuse) (Rodriguez-Garcia et al. 2011). It is also worth mentioning that some impacts caused by municipal wastewater treatment plants (MWWTPs) may also be produced due to the non-exploitation of the potential energy from organic matter and the fertilizer values of nutrients (Hospido et al. 2004; Law et al. 2013; Pretel et al. 2013).

In the context of integrated water resources management and more precisely of the wastewater management practices, it is important to develop and use impact evaluation methods that are able to capture (by identification, description and quantification) as easily as possible (from a methodological point of view) the complexity of the water-related impacts associated to wastewater treatment and discharges. This implies that these methods have to be capable to accurately describe, compare and prioritize among impacts (in various environmental compartments) and/or treatment processes, so as to enable treatment processes evaluation or site comparison.

It is important to mention the contributions of "*the life cycle methodology*", "*the footprint instruments*" and "*the environmental assessments*" for the efficient use of water resources. In this broad assessment field, researches have been developed (in parallel) to respond to river basin management needs by integrating them with specific issues of production and consumption at the water use cycle level (Boulay et al. 2013; Kounina et al. 2013; Ridoutt and Pfister 2012; Čuček et al. 2012). In this wider context of sustainability assessments in the water use cycle, the environmental component is of paramount importance due to the complexities of the water-related impacts and the need for scientifically founded actions and decisions in water resources management.

Under the broad term of *environmental assessments*, there have been developed and used several types of mandatory or voluntary procedures and methods with the scope of identifying, describing and evaluating the causes and effects of environmental impacts. As presented in Table 1, environmental impact assessment (EIA) is usually defined as a mandatory assessment procedure that analyses and evaluates the impacts that human activities can have on the environment (Toro et al. 2013). EIA uses different types of instruments and applies to different types of activities (projects and/or existing production and services processes) and has as main deliverable a form of environmental impact statement (EIS) (UNEP 2002). For the environmental impact evaluation, there are available both qualitative and quantitative impact evaluation methods that are being used to assign (qualitatively) or compute (quantitatively) numerical values for the environmental impacts (Buytaert et al. 2011; Ness et al. 2007; Singh et al. 2012).

The *life cycle assessment* (LCA) methodology standardized by ISO 14040: 2006 (ISO 2006a) and ISO 14044: 2006 (ISO 2006b) has gained an increasing interest from researchers and water professionals to be used on water/wastewater systems because it evaluates various aspects of water use cycle systems relying on advantages such as: the numerical characterization of impacts based on cause–effect relationships, the definition and characterization of multiple environmental impacts (Zhang et al. 2015; Corominas et al. 2013).

There are also some drawbacks of LCA that limit its advantages, and these refer to the data quality needed for a thorough LCA water study, as well as to some methodological issues in completely describing water-related impacts, within the well-established life cycle impact methodologies (Corominas et al. 2013; Koehler 2008). Traditionally, water resources are regarded in most of the LCA reports and studies as transport medium for useful products or pollutants, and in some of these studies, the impact of water resources use is being considered just as water consumption (Barjoveanu et al. 2014).

The water footprint (WF) instrument was introduced by Hoekstra in 2002 as a spatially and temporally specific indicator, showing when, where and how the water is used (directly or indirectly) and polluted, helping managers to identify the main water users and to associate different kind of agricultural, municipal and industrial water users in the system (Hoekstra 2003; Hoekstra and Chapagain 2008).

The *blue* water footprint is related to the surface and groundwater water resources use along the product supply chain; the *green* water footprint refers to consumption of rainwater (not as runoff), while the *grey* water footprint refers to

**Table 1** Classification of environmental impact assessment procedures and instruments

| Assessment instrument/ procedure | Applications (name of procedure) | Types of evaluated impacts | Methods and principles | | | | Assessment outcomes (environmental impact statement) |
|---|---|---|---|---|---|---|---|
| | | | Impact Identification | Impact Analysis (description) | Impact evaluation | | |
| | | | | | Qualitative methods | Quantitative methods | |
| Environmental impact assessment (mandatory procedure according to Directive 2014/52/EU) | Plans, programs, policies (Strategic environmental assessment) | Potential impacts | Yes | Yes, description of potential impact | Yes (e.g. interaction matrices, checklists) | No | (Strategic) Environmental Agreement |
| | New Projects (Environmental impact assessment) | Potential impacts | Yes | Yes, description of potential impact | Yes (e.g. interaction matrices, checklists) | Yes | Environmental Agreement |
| | Existing, operational activities (Environmental impact assessment) | Actual impacts | Yes | Yes | Yes | Yes (impact indicators, indexes) | Environmental Permit |
| Life cycle assessment (voluntary procedure according to ISO 14040) | Traditionally applied to Product systems,<br>Production processes and chains<br>New assessment approach: water use cycle evaluation | Potential (virtual) | Yes, trough impact classification of LCIA | Yes, through impact characterization (normalization and weighting) of LCIA | No | Yes, through impact characterization (normalization and weighting) of LCIA | Interpretation of results phase: environmental profiles, recommendation and scenarios |
| Environmental impact quantification indexes (including Grey Water Footprint) (voluntary procedures) | Product systems, Production processes<br>New approach: env. impact quantification | Potential (virtual) | Yes, (intrinsic) | Yes (intrinsic) | No | Yes, depending on impact definition (e.g. virtual volume of dilution water to reach objectives) | Environmental impact quantification indexes |

pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al. 2011).

The *Water Footprint Assessment* (WFA) is a methodology that addresses freshwater resources appropriation in a four-step approach, i.e. setting goals and scope, WF accounting (*blue, green* and *grey* WF), sustainability assessment and response formulation (Boulay et al. 2013).

In this study, three different environmental impact assessment instruments are being tested to evaluate the impacts caused by municipal wastewater discharges. These instruments refer to: environmental impact quantification (EIQ), the life cycle assessment (LCA) and the grey water footprint accounting (GWF). These instruments are developed and tested in a rather different and broader context than their traditional or conventional uses, which represent the main innovative aspect brought by this study. Thus, the proposed EIQ index considers for calculating the impact, the wastewater characteristics (flow and quality) simultaneously with the receiving river characteristics (flow and quality). The grey water footprint tool is used differently as compared to the traditional case, where it is employed to assess product systems. In our study, the grey water footprint is used to evaluate the local (virtual) impacts caused by wastewater discharge. Also, for this study, the life cycle assessment has been applied to the end-use phase of the water use cycle, i.e. the wastewater discharges.

The objective of this paper is to comparatively analyse these three assessment instruments (LCA, EIQ and GWF) by considering a common case study (a MWWTP) and to understand their (methodological) weak and strong points in capturing the impacts due to wastewater discharges. Such a comparative analysis is necessary to understand how the (individual) advantages provided by each of these instruments can be complimentarily used to improve an assessment framework for various stakeholders concerned with water use cycle management (regional water operators, water management authority, public authorities, research entities, societal organizations, etc.). This endeavour is particularly motivated for regions where new water-related legislation and targets have to be enforced in a short period of time, based on infrastructure development. The study considers, for the three methods implementation, the same type of water quality indicators for the effluents of the municipal wastewater treatment plant of Iasi (SC APAVITAL SA Iasi), in correlation with the indicators relevant for surface water quality where these wastewaters are discharged, all data being collected for 2012.

The main criteria in applying and comparing these methods are related to: (i) the overall data needed and the analysis of resulted impact categories, (ii) the relevance and the easiness of applying these methods for the assessment of actual impacts of municipal wastewater discharges considering the WFD objectives and specific legislation requirements, and (iii) the analysis of combined application of these methods, especially for assessing environmental impacts related to the development of the water system infrastructures of the regional water and wastewater treatment operators and the support for decision making.

## 2 Overview of studies for environmental assessment of wastewater discharges

Table 2 presents an overview of the recent studies that deal with the three types of instruments (LCA, EIQ, GWF) for *wastewater treatment* and/or the *water use cycle*, pointing out a limited number of cases that deal with the combined use of these instruments. These case studies refer to the assessment of wastewater treatment, selection of (advanced) treatment alternatives for improving the quality of effluent prior to discharge or wastewater recycling or reuse, sludge treatment alternatives.

Several research on LCA for wastewater treatment evaluation reviewed by Corominas et al. (2013) and Zhang et al. (2015) have demonstrated not only the growing interest for research in this field, but also the great diversity of these studies. The most important differences among the reviewed studies relate to: functional units, systems boundaries, impact categories and life cycle impact assessment methodologies, which greatly impair detailed study comparison and generalization of results.

Available literature on evaluating wastewater systems by LCA shows, in general, that removing more pollutants from discharged wastewater generates increased impacts especially in the energy-connected impact categories and that increasing attention should be directed towards advanced wastewater treatment technologies able to remove emerging (priority) pollutants (Corominas et al. 2013; Rodriguez-Garcia et al. 2011). In this context, the adaptation of existing methodologies to better represent regional local and even site-specific conditions in LCA studies (Zhang et al. 2015), together with improving data quality and reducing uncertainty represent major research directions in this field of LCA studies (Yoshida et al. 2014) are required.

Only few studies consider a comparison between LCA and other EIQ evaluations, Jegannathan and Nielsen (2013), approaching these issues in their review applied for enzymatic processes. EIQ is more advantageous because of its simplicity, but still has two important drawbacks that need to be considered in future environmental assessments: (1) it focuses on a single process ignoring the upstream production processes and (2) it uses single metrics and does not differentiate various effects induced in environment. Gutiérrez et al. (2010) studied the link between life cycle (LCA) and environmental impact assessment and emphasized that LCA requires large amount of data and generates large amount of results that can be difficult to be interpreted, and for this reason, LCA

**Table 2** Overview of studies for environmental impact assessment of wastewater discharges

| Authors, Publication year | Study focus/application |
|---|---|
| Life Cycle Assessment (LCA) | |
| Zhang et al. 2015 | Extensive review of LCA studies on biological wastewater treatment focused on environmental impact categories (LCIA results) |
| Lane et al. 2015 | LCA of Urban water systems, Australia |
| Mills et al. 2014 | LCA evaluation of Sludge treatment technologies in UK |
| Corominas et al. 2013 | Extensive review of 45 papers concerning with LCA of WW focused on methodological aspects of LCA studies |
| Montejo et al. 2013 | LCA of eight Mechanical – Biological Treatment -based waste management scenarios in Spain |
| Pretel et al. 2013 | LCA of submerged anaerobic MBRs |
| Tong et al. 2013 | LCA of wastewater from industrial park in China |
| Valderrama et al. 2013 | Comparative LCA of sewage sludge valorisation |
| El-Sayed et al. 2010 | LCA on Alexandria urban water system |
| Lemos et al. 2013 | LCA of Aveiro (Portugal) urban water system |
| Dodbiba et al. 2009 | Comparative LCA study on Removal of As from wastewater by adsorption |
| Environmental Impact Quantification (EIQ) | |
| Teodosiu et al. 2013 | Integrated impact and risk assessment of wastewater discharges from municipal/industrial/agricultural facilities by EIA |
| Cojocariu et al. 2012 | Integrated impact and risk Assessment of the agricultural and related industries by EIA |
| Barjoveanu et al. 2010 | Integrated impact and risk assessment of WWTPs for sustainable river basin management |
| Grey Water Footprint (GWF) | |
| Wang et al. 2013 | Assessment of freshwater consumption and impact of water pollution along industrial production chain from yarn to fabric (blue and grey WF) |
| Unger et al. 2013 | Blue, green and grey WF assessment in the TATA industries. |
| Shao and Chen 2013 | Water Footprint Assessment for wastewater treatment. Hybrid analysis and WF assessment; WWT |
| | construction, operation and demolition |
| Ene and Teodosiu 2011a;b | Assessment of the grey water footprint for wastewater discharges |
| Multiple / Combination of methods | |
| Morera et al. 2015 | Blue and grey WF calculation for 3 scenarios of wastewater treatment. WF and LCA framework comparison. |
| Garrido-Baserba et al. 2014 | LCA and DSS |
| Jefferies et al. 2012 | WF and LCA comparison on water consumption |
| Sala et al. 2013 | Report on WF as LCIA indicator for water consumption |
| Chen et al. 2012 | MFA and LCA; LCA and ERA |
| Gutiérrez et al. 2010 | LCA and multivariate analysis |

would better work in association with other environmental assessment tools such as methods for impact quantification that can include more accessible data sets, or the water footprint.

As it may be observed from Table 2, the environmental impacts of the wastewater treatment plants are in most cases based on the LCA evaluations and not by applying EIQ methods that quantify the environmental impacts, so as to consider the problems posed by the national/regional legislation referring to surface water quality in the context of integrated water resources management (Barjoveanu et al. 2010; Cojocariu et al. 2011; Teodosiu et al. 2012; Teodosiu et al. 2013).

The *water footprint* (WF) is an indicator, with geographic and temporal specificity, presenting water consumption volumes by source and polluted volumes by type of pollution; the determination of its components (*blue*, *green* and *grey*) is realized in the *water footprint accounting* stage. WF mainly depends on the local water system vulnerability and on the amount of water collected by producers and consumers within the same system (Hoekstra et al. 2011). However, the results of WF accounting are not completely informative with regard to local sustainability because WF provides only an evaluation of water abstraction or utilization, with no reference to local or regional conditions under which it was performed (Jeswani and Azapagic 2011). The *water footprint assessment* (WFA) is sought as a next step to WF accounting and is designed to support better water management, including its use and allocation, and focuses on a complex analysis of the environmental sustainability, economic efficiency and social equity of freshwater use and allocation (Boulay et al. 2013). However, it should be noted that the few research efforts for using the water footprint assessment as a sustainability assessment tool have primarily focused on the blue and green components of the WF targeting more the water use (consumption) impacts and far less the wastewater discharge impacts as indicated by the grey WF. Thus, Shao and Chen (2013) have performed an environmental and economic assessment of a wastewater treatment plant by calculating its WF components in the building and operation phases. In a recent study, Morera et al. (2015) have used the WFA methodology (blue and green components of WF) to evaluate the environmental impacts of a wastewater treatment plant in Spain.

Several studies have been developed for GWF accounting at different levels but mainly for production or product systems. For example, Hoekstra and Mekonnen (2012) have quantified and mapped at a high spatial resolution the green, blue and grey WFs within countries associated with agricultural production, industrial production and domestic water supply by estimating annual averages for the period 1996–2005. Franke and Mathews (2013) have assessed the grey WF within the cotton clothing supply chain based on the contamination of water resources through the chemicals applied in cotton cultivation. Only few examples of using the GF as an environmental assessment tool to evaluate surface water pollution impacts are available. Using real data collected from 22 wastewater treatment plants, studies realized by Ene and Teodosiu (2011a; b) were the first assessing the *grey* water footprint for wastewater discharges in Romania, considering the local conditions (natural background concentrations in a receiving water body and the ambient water quality standards for the receiving freshwater body).

For this study, we only perform the GWF accounting and not water footprint assessment, as our purpose is to better understand how to improve environmental assessment (as a component of sustainability assessment) and to enable methodological comparison with the other instruments. Furthermore, if for the blue and green components of the WF, various scarcity indexes have been proposed and used as sustainability indicators (or references), for the GWF, to our current knowledge, there is no such reference available for environmental sustainability assessment. A solution to this drawback would be to use as reference the GWF corresponding to the maximum allowed concentrations for ambient water quality, as presented in the next sections.

## 3 Case study and methodologies

### 3.1 Wastewater treatment system description and boundaries

The wastewater treatment plant of Iasi City is operated by SC APAVITAL SA which is the most important regional water operator in North-Eastern Romania, with responsibilities in water supply and wastewater management for more than 880,000 people at the county level and approx. 300,000 inhabitants of Iasi and the boundary area (Apavital 2012; Teodosiu et al. 2012). APAVITAL SA Iasi is rapidly increasing its operational area in Iasi and the surrounding cities and villages, which brings new technical and management challenges (Barjoveanu et al. 2011). In this context, this study presents a framework for a comparative assessment instruments that could be used by the regional water operator to set objectives and prioritize among technical solutions for its further development.

The Iasi municipal wastewater treatment plant (MWWTP) consists of two conventional mechanical–biological wastewater treatment lines which were recently fully refurbished and upgraded. The first wastewater line (line I in Table 3) comprises the conventional activated sludge technology, while the second line (the newest) comprises a two-step activated sludge process (first stage with very high organic load, second stage normal organic and sludge load) (line II in Table 3). Sludge disposal is performed by anaerobic mesophilic digestion of the excess primary and biological sludge together with biogas production followed by landfilling. At the present moment, a nutrient removal stage is under construction. The most important operational parameters of the Iasi WWTP are presented in Table 3.

The current technology of the Iasi MWWTP is able to remove pollutants to the levels presented considering the water quality indicators average values for 2012, as depicted in Table 4. In the same table, the water quality indicators for the reference, maximum allowed and river concentrations are also presented, data which are further used for the implementation and comparison of these methods.

### 3.2 LCA methodology

The life cycle analyses presented in this study is organized according to ISO 14040 specifications which comprise the following phases: *goal and scope definition, life cycle inventory compiling*, *life cycle impact assessment* and *results interpretation*. For this study, the system boundaries were defined for the 2012 situation, based on the actual configuration

**Table 3** Iasi MWWTP design parameters

| Parameter | Unit | Line I | Line II | TOTAL |
|---|---|---|---|---|
| Flow (dry weather) | $m^3/s$ | 1.8 | 2.4 | 4.2 |
| Removal capacities | | | | |
| Biochemical oxygen demand (BOD) load | kg/day | 24,000 | 32,000 | 56,000 |
| Chemical oxygen demand (COD) load | kg/day | 48,000 | 64,000 | 112,000 |
| Total solids load | kg/day | 24,000 | 32,000 | 56,000 |
| Total N load | kg/day | 3000 | 4000 | 7000 |
| Total P load | kg/day | 400 | 533 | 933 |
| Sludge management | | | | |
| Average sludge production | $m^3$/day | – | – | 128 |
| Average biogas production | $Nm^3$/day | – | – | 12,700 |

of the Iasi municipal wastewater treatment plant, and they include the wastewater treatment processes, the sludge treatment technologies and the auxiliary processes.

The goal and scope of the study is to evaluate the overall performance of the Iasi MWWTP in 2012, considering 1 $m^3$ of treated wastewater as the functional unit. The study considers only the actual operational phase of the Iasi municipal wastewater treatment plant *for all the evaluation instruments*, this being the reason why the construction and dismantling phases of its life cycle were not considered. Thus, the life cycle inventory contains data coming directly from this plant, data that have been determined during 2012 and processed subsequently as presented in Table 4 and in the Electronic Supplementary Material (Annex 1, LCI of the Iasi MWWTP).

LCIA has been performed using the midpoint ReCiPe method (version 1.12) for the categories presented in Table 5 (Goedkoop et al. 2012). Normalized results were obtained for an European weighting set. Furthermore, a second LCIA method Ecological Scarcity 2013 (1.02) was used to validate the results obtained with ReCipe. This method was used because it seems to be one of the closest LCIA methods to the other impact instruments used in this study. Ecological Scarcity 2013 considers the distance to target principle to calculate eco-factors for substances derived from environmental laws and regulations or political targets (Frischknecht and Büsser Knöpfel 2013).

### 3.3 Environmental impact quantification index methodology

The environmental impact quantification index proposed in this paper is based on previous studies performed by Barjoveanu et al. (2010), Ştefănescu et al. (2013) and Teodosiu et al. (2012), mainly towards integrating environmental impact with environmental risk assessment. For these previous studies, an environmental impact index was computed as a function of the impact magnitude (considering the flows of discharged wastewaters) and impact severity (considering the measured concentrations of water quality indicators) and natural quality state of the river (Teodosiu et al. 2013).

This instrument developed to quantify the environmental impacts due to MWWTP discharges takes into account two impact components. The first refers to the specific water quality indicators mentioned in national standards and which have to be fulfilled. The second one takes into account the flows of discharged wastewaters into surface waters. In this way, the instrument for environmental impact quantification considers the concentrations of water quality indicators and takes into account the local conditions such as: the quality of the receiving water body and the river flow. The methodology proposed in this study (EIQ index) considers the polluters loads (first term in Eq. (1)), a reference concentration (second term in Eq. (1)) and the ratio between the discharge (Qdet) and the river flows (Qriv) (third term). Depending on the reference concentration ($c_{ref}$), two situations may be distinguished when computing the environmental impact: (a) by considering the flow and quality of the receiving water natural state (water quality indicators determined at the river spring section) and (b) by considering the flow and quality of the receiving water body from just upstream of the discharge point of the MWWTP effluents. This methodology takes into account the ratio between the flow of discharged wastewater ($Q_{det}$) and the river flow ($Q_{riv}$) (Eq.(1)).

$$\mathrm{EIQ} = \frac{(c_{\mathrm{det}} \cdot Q_{\mathrm{det}}) + (c_{\mathrm{riv}} \cdot Q_{\mathrm{riv}})}{(Q_{\mathrm{det}} + Q_{\mathrm{riv}})} \cdot \frac{1}{c_{\mathrm{ref}}} \cdot \frac{Q_{\mathrm{det}}}{Q_{\mathrm{riv}}} \tag{1}$$

where:

EIQ is the environmental impact quantification index (dimensionless);

**Table 4** Selected water and wastewater quality indicators used in the assessments

| No. | Water Quality Indicator | No. of samples | Pollutant concentrations in: MWWTP effluent, $c_{det}$ | River spring section, $c_{spring}$ | River (just upstream discharge point), $c_{riv}$ | Max. conc. in effluent, $c_{max}$ (MAC) | Max. conc. Class II river quality, $c_{max\ ambient\ water}$ | Dilution Factor (GWF) | Flows: Wastewater, Qdet | River, Qriv |
|---|---|---|---|---|---|---|---|---|---|---|
| | | - | mg/L | mg/L | mg/L | mg/L | mg/L | - | $m^3/s$ | $m^3/s$ |
| 1 | Total suspended solids | 1138 | 14.82 | 56.48 | 19 | 35 | – | 0 | 2.34 | 2.995 |
| 2 | Chemical Oxygen Demand | 1138 | 37.13 | 20.134 | 31.00 | 125 | 25 | 1.26 | | |
| 3 | Ammonia nitrogen ($N\text{-}NH_4^+$) | 1135 | 0.32 | 0.068 | 1.62 | 2 | 0.8 | 0 | | |
| 4 | Nitrite ($NO_2^-$) | 265 | 0.68 | 0.040 | 0.196 | 1 | 0.1328 | 5.238 | | |
| 5 | Nitrate ($NO_3^-$) | 180 | 49.55 | 2.697 | 10.82 | 25 | 13.28 | 3.66 | | |
| 6 | Phosphorous (P) | 63 | 1.71 | 0.153 | 0.75 | 2 | 0.4 | 3.887 | | |
| 7 | Phenolics (Phe) | 39 | 0.04 | 0.012 | 0.024 | 0.3 | 0.005 | 0 | | |
| 8 | Copper ($Cu^{2+}$) | 5 | 0.057 | 0.006 | 0.37 | 0.1 | 0.03 | 0.803 | | |
| 9 | Zinc ($Zn^{2+}$) | 5 | 0.112 | 0.031 | 0.31 | 0.5 | 0.2 | 0 | | |
| 10 | Chromium ($Cr^{3+}$+$Cr^{6+}$) | 5 | 0.00264 | 0.009 | 0.081 | 1 | 0.05 | 0 | | |
| 11 | Total ionic iron ($Fe^{2+}$ + $Fe^{3+}$) | 50 | 0.45 | 2.028 | 0.36 | 5 | 0.5 | 0 | | |
| 12 | Nickel ($Ni^{2+}$) | 5 | 0.004767 | 0.007 | 0.006 | 0.5 | 0.025 | 0 | | |

$c_{det}$ is the measured concentration of each of the water quality indicators in the MWWTP effluent (mg/L);
$c_{riv}$ is the measured concentration of each of the water quality indicators upstream of the MWWTP discharge point (mg/L);
$c_{ref}$ is the concentrations of water quality indicators considered as reference for EIQ calculations. For *case* (*a*), the receiving water quality in its natural state (water quality indicators determined at the river spring section- $c_{spring}$ from Table 4) and $c_{ref}=c_{spring}$. For *case* (*b*), the receiving water quality indicators are considered for the river upstream of the MWWTP ($c_{riv}$ from Table 4) and $c_{ref}=c_{riv}$;
$Q_{det}$ is the discharged municipal wastewater flow ($m^3/s$);
$Q_{riv}$ is the river flow ($m^3/s$).

In this manner, the quantification of the environmental impacts of certain pollutants by considering also the local conditions becomes possible by considering also the local conditions, and not only the maximum allowed concentrations correlated with the WFD. The reference line in this case is EIQ = 1, when the polluters do not negatively influence the river water quality at local level. If the first term from Eq. (1) is higher than the measured concentration for the same quality indicator in the river spring section ($c_{spring}$) or measured concentration from upstream ($c_{riv}$), and the wastewater flow equals the river flow, then there is a negative impact upon the surface water quality and the aquatic ecosystem.

### 3.4 Grey water footprint accounting methodology

The *grey water footprint* (GWF) was calculated by using the methodology described in "*The Water Footprint Assessment Manual—Setting the Global Standard*" (Hoekstra et al. 2011), according to which, the *GWF* reveals the "appropriated waste assimilation capacity". The benefit of quantifying water pollution analysis in these terms (appropriated water volumes) is that it aggregates several types of pollution indicators into a single denominator or index, which is the adequate volume of water for waste assimilation (Hoekstra et al. 2011).

In this context, the GWF represents the virtual dilution of the wastewater effluent so as to meet the national quality standards for the receiving river. According to Hoekstra et al. (2011), the grey water footprint for point pollution sources can be calculated as presented in Eq. (2): the effluent flow ($Q_{det}$) multiplied by the pollutant concentration in the effluent ($c_{det}$) minus the actual concentration of the intake water ($c_{riv}$), divided by the difference between the ambient water quality standard (the maximum acceptable concentration $c_{max\_ambient\_water}$) for that pollutant and its natural background concentration in the receiving water body ($c_{ref}=c_{spring}$).

**Table 5** LCIA impact categories

| Abbr. | Impact category ReCiPe 1.12 | Characterization units | Abbr | Impact category Ecological Scarcity 2013 | Unit |
|---|---|---|---|---|---|
| CC | Climate change | kg ($CO_2$ to air) | WT | Water resources | UPB |
| OZ | Ozone depletion | kg (CFC-11 to air) | ER | Energy Resources | UPB |
| HT | Human toxicity | kg (14DCB to urban air) | MR | Mineral Resources | UPB |
| POF | Photochemical oxidant formation | kg (NMVOC to air) | LU | Land use | UPB |
| PMF | Particulate matter formation | kg (PM10 to air) | GW | Global Warming | UPB |
| IR | Ionizing radiation | kg (U235 to air) | OZ | Ozone layer depletion | UPB |
| TA | Terrestrial acidification | kg (SO2 to air) | AP | Main air pollutants and PM | UPB |
| F-Eu | Freshwater eutrophication | kg (P to freshwater) | C-Air | Carcinogenic substances into air | UPB |
| M-Eu | Marine eutrophication | kg (N to freshwater) | HM-Air | Heavy metals into air | UPB |
| TET | Terrestrial ecotoxicity | kg (14DCB to industrial soil) | WP | Water pollutants | UPB |
| FET | Freshwater ecotoxicity | kg (14DCB to freshwater) | POP | POP into water | UPB |
| MET | Marine ecotoxicity | kg (14DCB to marine water) | HM-Wat | Heavy metals into water | UPB |
| ALO | Agricultural land occupation | $m^2\ year^{-1}$ (agricultural land) | PEST | Pesticides into soil | UPB |
| ULO | Urban land occupation | $m^2a$ | HM-Soil | Heavy metals into soil | UPB |
| NLT | Natural land transformation | $m^2$ | RAD-Air | Radioactive substances into air | UPB |
| WD | Water depletion | $m^3$ | RAD-Wat | Radioactive substances into water | UPB |
| MD | Metal depletion | kg Fe eq | Noise | Noise | UPB |
| FD | Fossil depletion | kg oil eq | Waste | Non radioactive waste to deposit | UPB |
| | | | RAD-waste | Radioactive waste to deposit | UPB |

$$GWF = \frac{c_{effl} - c_{act}}{c_{max} - c_{nat}} \cdot Q_{effl} = \frac{c_{det} - c_{riv}}{c_{max\_ambient\_water} - c_{spring}} \cdot Q_{det} \qquad (2)$$

Where:

GWF is the grey water footprint ($Mm^3$/month)
$C_{effl} = c_{det}$ is the measured concentration of each of the water quality indicators in the MWWTP effluent (mg/L);
$c_{act} = c_{riv}$ is the measured concentration of each of the water quality indicators upstream of the MWWTP discharge point (mg/L);
$c_{max} = c_{max\_ambient\_water}$ is the concentration for ambient water quality standard which is the maximum allowed concentration for a given river quality (mg/L);
$c_{nat} = c_{spring}$ is the natural background concentration, *i.e.*-concentration in the spring section of the river, mg/L;
$Q_{effl} = Q_{det}$ is the wastewater flow, $m^3$/month.

In Eq. (2), the component before $Q_{effl}$ represents the "*dilution factor*", and it expresses the number of times that the effluent flow needs to be diluted with ambient water to attain the maximum allowed concentration level. It is important to identify the water quality standards and the natural concentrations (both vary for surface and groundwater bodies) that will be applied in grey water footprint accounting. Both $c_{ref}$ and $c_{max\_ambrient\_water}$ need to be established according to the national legislation for each of the pollutants contained in the effluent discharged to the receiving water bodies. In this case, because data were available, we have used the natural background concentrations ($c_{nat} = c_{spring}$ from Table 4) and the multi-annual average concentrations in the spring section of the receiving river. For the maximum allowed limits ($c_{max\_ambrient\_water}$), we have used the values for class II water quality as defined by the Water Framework Directive and presented as guidelines in the national legislation (Environmental Ministry Order 161/2006) (Romanian Government 2006; Teodosiu et al. 2013).

Due to the multidimensional character of wastewater quality, the *total grey water footprint* ($GWF_{tot}$) was estimated to be the maximum between the monthly virtual volumes of water required for the dilution of all the analysed pollutants (Eq. (3)) since this kind of assessment takes into consideration both the size of the wastewater volumes impacts and pollutant concentrations and the vulnerability of the receiving water body.

$$GWF_{tot} = \max(GWF_i), (\text{volume}/\text{time}) \qquad (3)$$

## 4 Results and discussion

### 4.1 Life cycle assessment of the Iasi MWWTP

The general environmental profiles of the Iasi MWWTP are presented in Fig. 1a by using the ReCiPe method (version 1.12) and Fig. 1b by using the Ecological Scarcity 2013 method.

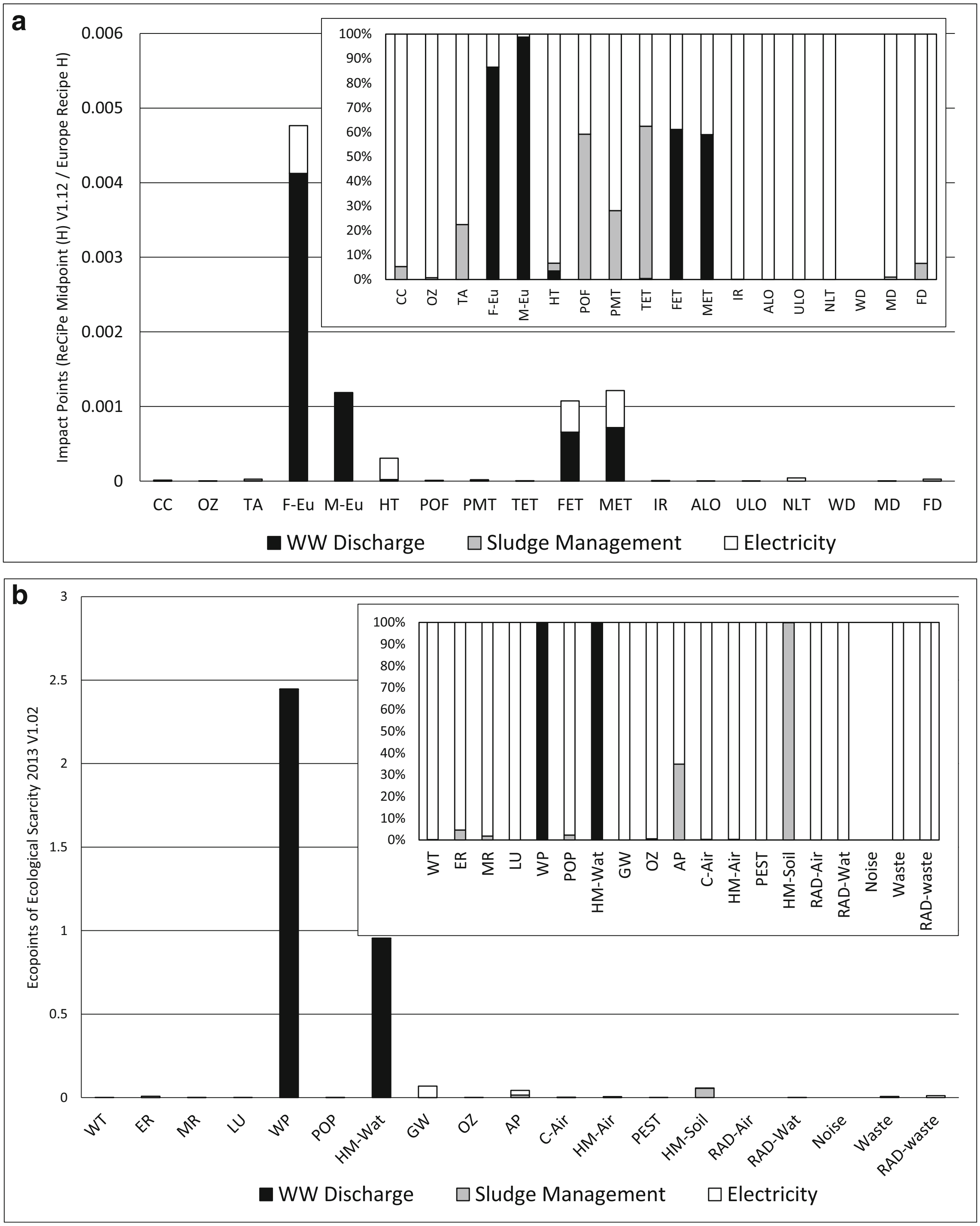


**Fig. 1** **a** Environmental profile of Iasi MWWTP by using the mid-point ReCiPe method. **b** Environmental profile of Iasi MWWTP by using the Ecological Scarcity 2013 method

When using the midpoint ReCiPe method (Fig. 1a), the water-related impact categories (e.g. Freshwater & Marine Eutrophication and Freshwater & Marine Ecotoxicity) appear as the most relevant ones due to the discharge of the treated wastewater. Conversely, all the other impact categories are less relevant for the European normalization set that the midpoint ReCiPe uses, but as it can be observed in the snippet of Fig. 1a (characterisation results), the electric power consumption and sludge management processes contribute to the impacts of these other categories. In terms of absolute impact values, the midpoint ReCiPe LCIA shows a contribution of the Iasi MWWTP of 0.00197 kg eq P for F-Eu and

0.012 kg eq N for M-Eu and contribution of 0.144 kg $CO_2$ eq for climate change, which are in the range of values presented by Loubet et al. (2014) in a review that evaluated 117 LCA studies of water systems.

When using the Ecological Scarcity 2013 method (Fig. 1b), the most important impact categories are the water pollution (WP) and heavy-metal into water (HM-Wat) due to pollutants discharge. In the other impact categories, the most important contributor is the electric power consumption, while the sludge management processes contribute only to the *main air pollutants and PM* (AP) and the *heavy metals into soil* (HM-soil).

A closer look at the water-related impact contributions of the Iasi MWWTP would reveal that, according to the ReCiPe method, eutrophication is due to phosphorus species (F-Eu) and nitrogen species respectively (M-Eu), while in the Freshwater Ecotoxicity category, the calculated impact is due only to the heavy metal species, with no contribution from organic pollutants, as data for specific organics was unavailable. In the case of the Ecological Scarcity method, water-related impacts are grouped into three categories: Water pollution (to which contribute most of the organic waterborne emissions, expressed in our case as COD, but also the other eutrophication contributors as N and P species), POPs into water (for which unfortunately, in our case no data were available) and Heavy metals into water.

In this respect, it is important to note that there is a difference between how impacts are expressed by current LCA methodologies and what type of water quality indicators should be monitored by the MWWTPs. For example, the remnant organic pollution in discharged wastewaters is measured usually by a global indicator (COD), but this is not accounted for in ReCiPe, which, in turn, considers a multitude of organic compounds as contributors to water pollution (FET category). Conversely, the Ecological Scarcity 2013 method not only accounts the COD in the water pollution category, but also considers other organic species in the POPs of the water category. It is relevant to note that there is an increasing research interest for identifying and quantifying impacts (Ratola et al. 2012) due to remnant organic pollution in wastewater discharge and to include them into LCA studies (Alfonsín et al. 2014).

This difference between the actual MWWTPs monitoring and the LCIA requirements induces problems related to the data quality for LCA studies because usually the monitoring frequency for each indicator is imposed by the legislative/water authority requirements (Table 3). Thus, one may discover that indicators that are monitored on a routine basis by the MWWTP for operational or environmental purposes are just partially connected to the impacts in LCIA methodologies (e.g. COD as global indicator for organic pollution is not represented in ReCiPe in the corresponding relevant impact categories, i.e. eutrophication), while infrequently monitored indicators are given a greater importance in the same LCIA methodologies (e.g. the heavy metals and POPs).

This analysis shows that, for the Iasi MWWTP, the most important impacts are given by the wastewater discharges and the electricity consumption, but it is important to note that the two LCIA methods do not account for the local aspects in computing the MWWTP impacts, fact which limit the interpretation of results, especially for non-LCA professionals.

Although there is a growing interest in the LCA community to better represent regionalized impacts in LCA studies (Loubet et al. 2014; Zhang et al. 2015), these efforts are mainly conducted towards representing consumptive water uses (Kounina et al. 2013) and to a lesser extent towards the the pollution-related water impacts (Gallego et al. 2010). From a MWWTP practitioner point of view, regionalized impacts would certainly improve LCA usefulness, as it would be important that the local conditions should be better represented in calculating impacts to enable better decisions regarding wastewater management, but at this moment, frameworks for calculating site-dependant impacts for water pollution are unavailable.

To overcome the current limitation of the LCA methods in describing local impacts, two scenarios have been created to be used as impact references in analysing the results and to provide a minimal comparison framework with the other two methods used in this paper. One scenario considers the wastewater discharge at MAC levels and the other one considers wastewater discharge with no treatment.

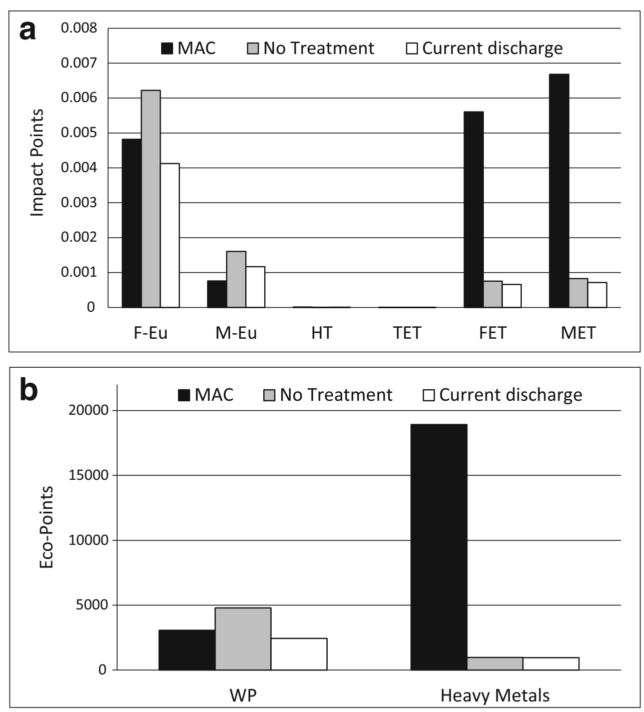


**Fig. 2** **a** No treatment, MAC and current situation comparison using mid-point ReCiPe 1.12. method. **b** No treatment, MAC and current situation comparison using Ecological Scarcity 2013 method

In Fig. 2a, a comparison of relevant impact categories are presented by using the midpoint ReCiPe method which shows that, in general, the current discharge has lower impacts than the maximum allowed ones, with the exception of M-EU, where due to the very high nitrate concentrations (approx. 2 times higher on average than the MAC, as presented in Table 4), the current discharge impact is higher than the MAC one. In the human toxicity (HT) and terrestrial ecotoxicity (TET) categories, the impacts are negligible compared to the other categories. In the FET and MET categories, where the impact is attributed to heavy metals, one may observe that the MAC levels are very permissive, and there is little difference between the treated and untreated effluents. This trend is confirmed when using the ecological scarcity method (Fig. 2b). Also, in Fig. 2b, in the water pollution category, the current discharge levels are close to the MAC ones, but not overcome.

## 4.2 Quantification of the environmental impacts of the Iasi MWWTP

The environmental impact generated by the effluent of the MWWTP was assessed by considering the measured concentrations of 12 water quality indicators monitored in the effluent of MWWTP over 2012, upstream of wastewater discharging point and in the natural state of the river spring section, as presented in Table 4.

The environmental impact quantification method highlights the major hotspots and identifies and prioritizes the pollutants for which prevention and control activities should be considered as emergency. The environmental impact index values obtained from Eq. (1) for each water quality indicator offer an indication about the pollutants that cause impacts on surface water and contribute to the identification and prioritization of environmental issues and emergency measures inside the MWWTP.

The calculated impact EIQ values were compared against two distinct situations (for both, $EIQ_{ref} = 1$):

a. When the reference section was considered the river spring section (natural background concentrations) and
b. When the reference section was considered the river section just upstream of the Iasi MWWTP discharge point.

For both situations, in the case of impact index lower or equal to 1, there are no negative effects induced on the environmental quality (surface water), while values above 1 indicate a pollution contribution for that given indicator, but with different significance for the two situations.

The results of environmental impact quantification of the effluent of municipal WWTP revealed that the major negative impact is caused by the pollution with nitrogen and phosphorous compounds, phenolics and heavy metals, in the case of considering as reference the quality of river spring section

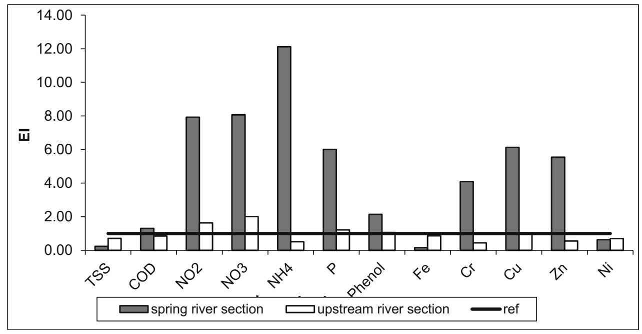


**Fig. 3** Environmental impacts (EIQ) (compared to the quality of the river spring section and to the upstream of the discharge point section)

(Fig. 3). When the quality of the upstream river section is considered as reference, the major negative impact is caused by pollution with nitrogen and phosphorous compounds and phenolics. Even if the monitored pollutants in the effluent are under the maximum allowed limits, the impact indexes quantify the individual contribution of the polluter (Iasi MWWTP) and indicate some negative effects on surface water as compared with its natural status.

The results presented in Fig. 3 show that, for the Iasi MWWTP, impacts are generated by nitrate, nitrite, phosphorous and phenolics, as quantified for both situations. This means that for impacts higher than 1, even if the MWWTP effluent is within the MAC limits, there is a pollution contribution of the Iasi MWWTP to the receiving river which can be interpreted differently, but with respect to the local river conditions (flow and quality).

From a methodological point of view, the results demonstrate the flexibility of this environmental quantification method, enabling different assessment perspectives to be considered. For example, in the first situation (case **a**), calculated values indicate the individual contribution of a given polluter as compared to the natural background concentrations of the river and could be used to compare several polluters that discharge in the same water body. In the second situation (case **b**), the impact values indicate the individual contribution of a polluter as compared to the local conditions (at the discharge point) and could be used to identify immediate measures or to quantify specific contributions (in fact, impact levels under the $EIQ_{ref}$ value of 1 indicate a positive environmental impact by dilution).

Also, it is important to note that the case presented in this study is based on measured water and wastewater quality data for 2012, both for the discharge point and on the river. In this respect, data availability can represent a limitation for the method, but this can be overcome by coupling this method with various other instruments like on-line monitoring and water quality modelling.

This methodology for environmental impact quantification applied on the case of surface water presents the main advantages that the individual contribution of each pollution source is quantified and a master plan for water management at river basin scale, or national level, could be elaborated considering the individual negative effects induced on surface water and the compulsory measures and actions that need to be assured by each polluter in order to preserve the natural river water quality status.

### 4.3 Grey water footprint accounting for the Iasi MWWTP

The grey water footprint accounting was based on the methodology described in the "Water Footprint Assessment Manual" (Hoekstra et al. 2011). However, for the grey water footprint accounting, the water quality standards and the natural concentrations of the receiving water body were identified in accordance with the Romanian legislation (Romanian Government 2006). The dilution factor highlights the pollutant contribution to the effluent quality, although it does not have any influence on the receiving water quality amelioration. The dilution factor is higher as the concentration of pollutants in effluents and in the receiving water body is higher. According to this methodology, negative dilution factors are possible, which would mean discharging water at a higher quality than the receiving water body. In our case, the negative dilution factors were adopted as zero, attesting the fact that those pollutants do not negatively influence the receiving water body ($c_{det} < c_{riv}$). The dilution factors for the analysed pollutants at the Iasi MWWTP plant are presented in Table 4.

The dilution factors associated with nutrients (nitrogen compounds like $NO_2^-$ and $NO_3^-$ and total phosphorus) are the highest among the calculated ones, clearly denoting the urgent need that the municipal wastewater treatment plant is upgraded for nutrient removal.

The calculated positive (>0) grey water footprint values (actual GWF in Fig. 4) do not indicate that the water quality standards are exceeded, but emphasizes that the assimilation capacity of the receiving river has been partially consumed.

The results show that the total GWF is related to the nitrogen compounds discharged into the natural receiver, with a maximum value of 31.82 $Mm^3$/month, representing the virtual required volume of water needed to dilute the receiving water body in order to maintain its water quality to a level that corresponds to the Water Framework Directive objectives and will not influence the downstream consumers, the ecosystems or the human health.

These results are compared in the same figure to a hypothetical scenario according to which all wastewater effluents would be discharged at the maximum allowed concentrations (GWF-MAC series in Fig. 4, $c_{det} = MAC$), as presented in the Governmental Decision 352/2005 (Romanian Government 2005). This comparison shows that, for most indicators, the actual grey water footprint is much smaller than the one theoretically allowed by the water discharge permit. However, this is not the case for nitrate and total phosphorous which have higher GWFs than the GWFs corresponding to MACs, which is consistent with the results obtained through the other instruments and show again the nutrient problem at the Iasi MWWTP in 2012.

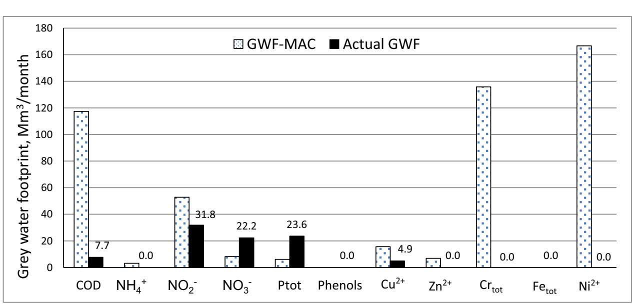


**Fig. 4** GWF results for the analysed WWTP

### 4.4 Discussion

The environmental impacts computed with the three assessment instruments and presented above in a case study applied for the Iasi MWWTP discharges by using data from 2012 are consistent in terms of impact categories (or types), as all instruments show problems with nutrients (nitrogen and phosphorous compounds) and toxic substances (mainly heavy metals) discharges. This is fairly important since the three instruments have different impact definitions, as well as different reference systems. While LCA quantifies environmental impacts as the effects (or damages) that different environmental compartments may suffer (e.g. toxicity or any other type of harm), the environmental impact quantification method and the grey water footprint quantify impacts by comparing the discharged pollution (or load) to a reference pollution level which is related to the quality of the receiving water body and hence to legislative limits.

This is one of the main differences between these assessment methods: LCA is completely independent in time and space, its impacts depending only on the dimension (pollution load) and effect type, while the other two instruments quantify impacts considering the local conditions like the quality of the receiving water body (upstream of the discharge points or at the river spring) and the corresponding legal requirements. The environmental impact quantification method takes into consideration the impact magnitude (as the net pollutant load to the river), the initial river quality, as well as the wastewater and river flows. This is somehow similar to the grey water footprint instrument which considers the effluent and river quality, river quality standards and the wastewater flow.

The results presented in this study have enabled a qualitative comparison of these three assessment methods applied to the same case study (Iasi MWWTP), this analysis results being also summarized in Table 6.

**Table 6** Environmental assessment methods comparison

| Method | Life cycle assessment | Environmental impact quantification | Environmental impact quantification |
|---|---|---|---|
| Impact quantification principle | Causality chain (emission, transport, effect, damage) | Individual polluter contribution to river pollution (load) | Impact = virtual water volume needed to dilute pollutant loads to acceptable levels |
| Impact definition (meaning) | Impact (damage) = Magnitude×dose×exposure | Impact = magnitude (loads)× severity (receiving river status) | Virtual water volume needed to dilute pollution to acceptable levels |
| Impact Classification System (reference system) | •Characterisation factors and Reference substance (impact) within a specific impact category | •River natural water quality (spring section)<br>•River water quality upstream of the discharge point | •River natural water quality (spring section) |
| Data requirements | Emissions to air, water (quality indicators)<br>Waste flows | Wastewater quality indicators | Wastewater quality indicators |
| | Wastewater flows<br>Electricity use | Water quality indicators | Water quality indicators |
| | Natural gas consumption<br>Materials use | Wastewater Flows | Flows |
| *Strong points* | •Generation of complex environmental profiles | •Characterization of local impacts | •Characterization of local impacts |
| | •Comparison among different impact categories and different environmental components | •Characterization of individual pollution contribution | •Characterization of individual pollution contribution |
| | •Technical and economical performance evaluation tool | •Consideration of legislative frameworks | •Consideration of legislative frameworks (methodology) |
| | | •Rapid assessment | •Rapid assessment |
| | | •Versatility and adaptability | •Versatility |
| | | •May be applied by MWWTP or Water authority specialists (provided with an established methodology) | •May be applied by MWWTP or Water authority specialists (provided with an established methodology) |
| *Weak points* | •Complex data requirements | •Method sensitivity depends on data quality (no. of water quality samples) | •Method sensitivity depends on data quality (no. of water quality samples and no. of indicators) |
| | •Inconsistent impacts definition in LCIA methods<br>•Rigid assessment framework | •The environmental profile is limited to the water component | •The environmental profile is limited to the water component |
| | •No correlation to local conditions or legislative requirements | | |
| | •May be applied only by LCA specialists | | |
| *Development status and integration* | •Well developed for MFA and product systems<br>•In development for water systems and improved water-related impacts (international standard development) | •Initial development | •Well developed for product systems<br>•In development for WWTP assessment |

*4.4.1 Methods relevance*

For this analysis, the relevance is an assessment criterion that considers how the three methods respond to the scope of the environmental assessment and the usefulness of the results for various stakeholders. The scope of some of the environmental assessments performed at MWWTPs is to measure the impacts induced to surface waters by the wastewater discharge and/or subsequently to assess the environmental performance or sustainability of the treatment plant. As presented also in Table 6, the three methods discussed in this study give different meanings to environmental impacts which can be relevant or useful in different assessment frameworks or for different performance criteria.

In practice, the MWWTP impacts to surface waters (and subsequently their performances) are accounted by both water authorities and wastewater managers by using the legal requirements as a reference system which defines maximum allowed concentrations, which indicators should be monitored and with which frequency. From this point of view, the life cycle impact assessment methodologies (LCIAs) are limited, as there is no correlation between their impact values and the legal references, while the other two instruments link the environmental impact directly to the legal requirements. In this sense, the LCIA methodologies are of little help in assessing the impact of wastewater discharges in relation to the WFD objectives or to other water quality legislative requirements.

On the other hand, LCIA methodologies measure impact as the (potential) damage for different environmental components and enable an objective comparison between impacts in different categories in complex environmental impact profiles. This brings another dimension to the performance (or sustainability) assessment and it is important for the MWWTP sustainability. As it was demonstrated by some research groups, the improvement of the effluent quality induces more pollution to other impact categories (especially to the global warming potential).

### *4.4.2 Data requirements*

As with any assessment instrument, the output of all three instruments depends on the quality of the input data. Among the three, LCA requires large amounts of data in multiple areas in order to compile a reliable life cycle inventory. With respect to the wastewater discharge impacts, we should note that data relevance and coverage is particularly important for all the methods. As indicated in the previous section, there is a serious gap between the data monitored by MWWTPS as required by legislation (indicators and frequency) and the impacts calculated through LCIA methods. Because the grey water footprint calculates the impact by comparing dilution factors for different water quality indicators, the method relevance is impacted by the number of available indicators.

The versatility and adaptability of the methods is very important to enable transferability and generalization. The environmental impact quantification tool and the grey water footprint are adaptable, as it is possible to change references and assessment frameworks and objectives to depict local impact conditions. This is harder for most LCIAs because they employ multiple impact categories for which it is difficult to calculate local characterization and normalization factors.

The strong and weak points of each method as depicted from this comparative study are also presented in Table 6.

## 5 Conclusions

The main objective of this paper was to assess the environmental impacts of a municipal wastewater treatment plant from Romania by using three different impact assessment instruments: (1) life cycle assessment (LCA), (2) environmental impact quantification (EIQ) and (3) grey water footprint (GWF) and to critically compare these three methodologies from a practical and applicability point of view in order to support various water management stakeholders and especially the wastewater treatment operators.

For this purpose, this study has been developed around a single case study (Iasi MWWTP) to enable comparison of the three impact assessment methodologies. The three methodologies present rather different approaches to environmental impact definition and quantification due to municipal wastewater discharge as it was presented in the *overview of methods development and application*. LCA quantifies impact along a causality chain, and it is virtually time and space independent; the EIQ instrument assesses the local wastewater treatment discharges by comparing the actual pollutant contributions (inputs) with the river natural background concentrations, and finally, the grey water footprint measures the virtual water volume needed to dilute pollution to harmless levels, considering the legislative requirements.

Although the three methodologies have different principles for environmental impact quantification, the results have shown that, for this case (the Iasi MWWTP in Romania), most impacts to surface waters are given by the nutrients (nitrogen and phosphorous compounds) in wastewater which could induce a eutrophication impact and to a lesser extent by pollutants responsible for toxicity impacts in the receiving water body.

However, the analysis of results has demonstrated the weak and strong points of each assessment method and has emphasized the necessity for improving each method for their complimentary and integrated use. For example, widely used LCIA methodologies have to be improved to better represent water-related impacts (including waterborne emissions) and could benefit from the other two impact assessment instruments to better represent local conditions. On the other hand, the environmental impact quantification instrument and the grey water footprint accounting methodology could be improved by considering the standardized assessment framework provided by the LCA methodology. Furthermore, the result analysis and discussion pointed out that at least for two stakeholders involved in wastewater management (wastewater operator and management authority), the legal requirements have to be considered in the assessment.

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*Environmental and Human-related Impacts and Risks in the Water Use Cycle*" (WATUSER).

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