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Systemic eco-efficiency assessment of meso-level water use systems

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Abstract

Eco-efficiency has recently become an important concept of environmental decision making, serving as a policy objective and, if linked with resource efficiency, can be a measure of progress towards sustainability. The need for improving eco-efficiency leads to the challenge of identifying the most promising alternative solutions which improve both the economic and the environmental performance of a given system ("eco-innovations"). A methodological framework for the eco-efficiency assessment of a water use system at the meso level has been developed in the context of the EcoWater research project and consists of four distinct steps. The first step leads to a clear, transparent mapping of the system at hand and the respective value chain, while the second step provides the means to assess its eco-efficiency, following a life-cycle oriented approach using the midpoint impact categories. An important novelty is the distribution of economic costs/benefits and environmental pressures over different stages and stakeholders in the value chain. The third step includes the selection of innovative technologies, which are assessed in the last step and combined with mid-term scenarios in order to determine the feasibility of their implementation.

The proposed methodological framework has been applied to eight alternative water use systems, revealing all their environmental weaknesses and identifying potential opportunities for eco-efficiency improvement. At the same time, through the systemic approach all the involved actors are urged to cooperate in order to (a) propose and build innovative technological solutions that will improve the overall eco-efficiency of the system; and (b) make suggestions on the necessary policy framework that will facilitate and promote their uptake. This ensures that upstream decisions in the value chain are coordinated with downstream activities and all potential synergies are identified, leading to the creation of "meso-level closed resource loops" and thus the promotion of a circular economy.

Keywords: systemic eco-efficiency, water use systems, value chain, eco-innovation

1 INTRODUCTION

Water is a critical resource for all activities in a human society, with agriculture, industry, energy production and public water supply being the most important ones. It

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is estimated that about 3000 liters of water are required in order to cover the daily food needs of one person, (GWP, 2014). On average, 44% of total water abstraction in EU is used for energy production, 24% for agriculture, 17% for public water supply and 15% for industry. The importance of water as input to most production processes is also confirmed by the fact that while the world population has tripled in the 20th century, the global water usage has increased six-fold (Abra, 2012).

Population growth, urbanization and industrialization are linked with the increasing demand for water and have serious consequences on the environment and human health. According to the World Water Council, 23 countries will face absolute water shortage in 2025 and another 50 (with over 3,000 million total population) could suffer from water stress by the same time (Abra, 2012). Furthermore, over 80% of wastewater used worldwide is not collected or treated, leading to more than 3 million premature deaths annually from water-related diseases in developing countries (UNWATER, 2009).

Thus, there is need for monitoring and improving water use systems by identifying the most promising alternative solutions which improve both its economic and its environmental performance ("eco-innovations"). An eco-innovation can be defined as an intervention in a given physical system that reduces the use of natural resources and decreases the release of harmful substances into the environment, and its implementation results in both economic and environmental benefits, improving the overall eco-efficiency of the system.

Recent studies have shown that there is a wide range of available technical measures to save water and to improve its quality. However, the uptake of water-related innovations remains almost exclusively driven by regulations and their assessment is primarily based on water efficiency gains. Furthermore, interventions in complex physical systems (such as the water-use systems) may lead to large-scale transformations, which could affect all the heterogeneous actors involved with conflicting interests. Hence, a systemic approach is required, which will incorporate both the physical structure of the system and the rules governing the operation, performance and interactions of the system components.

The paper introduces the concept of a meso-level water use system and present a methodological approach in order to assess its eco-efficiency, developed within EcoWater Project, a Research Project supported through the 7th Framework Programme of the European Commission.

2 MESO LEVEL WATER USE SYSTEM

In a typical water use system, freshwater is abstracted from a source, treated and then distributed to different users. Each user consumes certain amount of water, satisfying specific quality requirements, along with other resources, for the production of one or more products/goods or/and the provision of one or more services. Wastewater from each user is collected and treated before being disposed into the environment.

A typical sustainability issue, arising in water use systems with competitive use sectors, is the allocation of water among the uses, by fulfilling the demand in an optimal way

(Figure 1). Optimization may refer to the minimization of the resource deficit (in water scarcity conditions) or the cost related to the use of the resource (e.g. the cost for water abstraction and distribution). Methodologies that are used to analyse this type of issues are based on resource balance concepts (Manoli, et al., 2005) and network optimization algorithms (Manoli, et al., 2001).

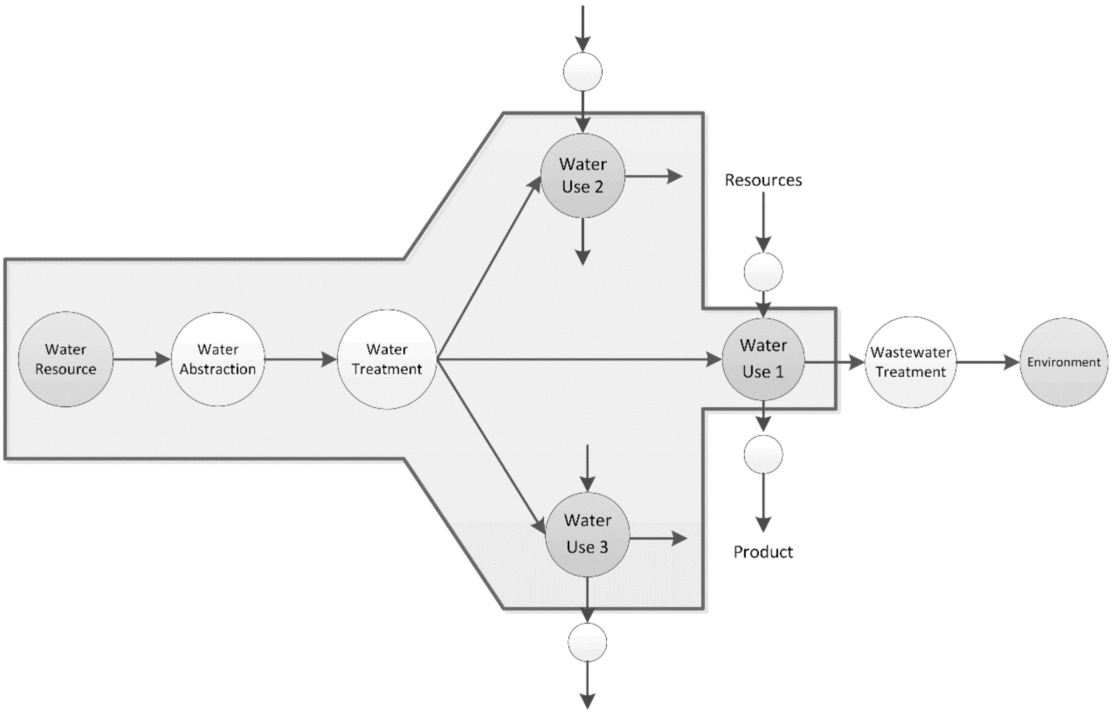

Figure 1. Water allocation to different uses

On the other hand, a sustainability issue, common in all production systems (Figure 2), is the efficient use of resources for providing goods or services. Resource efficiency aims at minimizing the use of the required resources while reducing the impact on the environment (Jonsen, 2013). Such systems are usually analysed by Life Cycle Impact Assessment (ISO, 1997; ISO, 2006; JRC, 2010; JRC, 2011) and Life Cycle Cost Analysis (Langdon, 2007), methodologies that focus on the production chain of the examined good or service, encompassing the resources required in the production processes as well as the final product.

The EcoWater project looks at the meso-level water use system (Dopfer, et al., 2004) that combines the typical water supply chain with the corresponding water use chain (Figure 3). The meso level can be defined as an intermediate scale between the micro and the macro level and offers an additional means of interpreting the eco-efficiency indicators. The macro level represents the national framework and conditions applying to all players and consists of the legal, economic and environmental parameters that significantly affect the water system. The micro-level, on the other hand, refers only to single unit and provides the basis for the evaluation of the direct effect that a specific technological option will have on it. Furthermore, the meso level can act as an intermediate step in technological transition between the technological niches (in the micro-level) and the wide adoption (or rejection) of new technologies (in the macro-level).

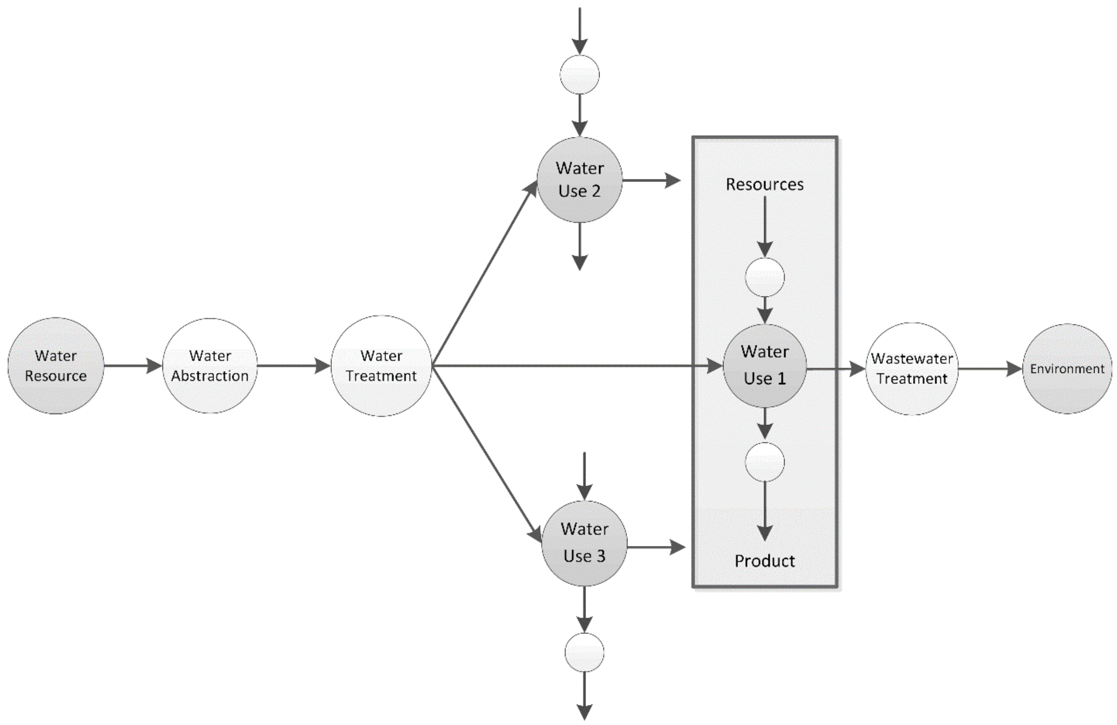

Figure 2. Efficient use of resources in a water use system

It combines a specific water use with all the processes needed to render the water suitable (both qualitatively and quantitatively) for this use, and the treatment and discharge of the generated effluents to the environment. It is not limited to the production chain of a specific enterprise or firm, but it considers the whole water cycle of the analysed system from abstraction to disposal. It incorporates both the physical structure of the system and the rules governing the operation, performance and interactions of the system components. It provides a concrete, comprehensive and accurate assessment of the economic and environmental performance of both each actor separately and the system as a whole. The analysis on the meso-level also takes into account the interdependencies and the economic interactions between all the heterogeneous actors involved in these two chains (e.g. between water service providers and users). It also involves the sharing of resources, services and by-products among the actors (symbiosis) in order to add value and reduce costs (Figure 3). Studying the value chain governance helps to identify the possible leverage points for policy initiatives (Humphrey & Schmitz, 2001), by pointing out the environmentally or economically weak actors/stages. It also allows understanding the profit distribution along the actors of the chain and addressing all the distributional issues that may arise.

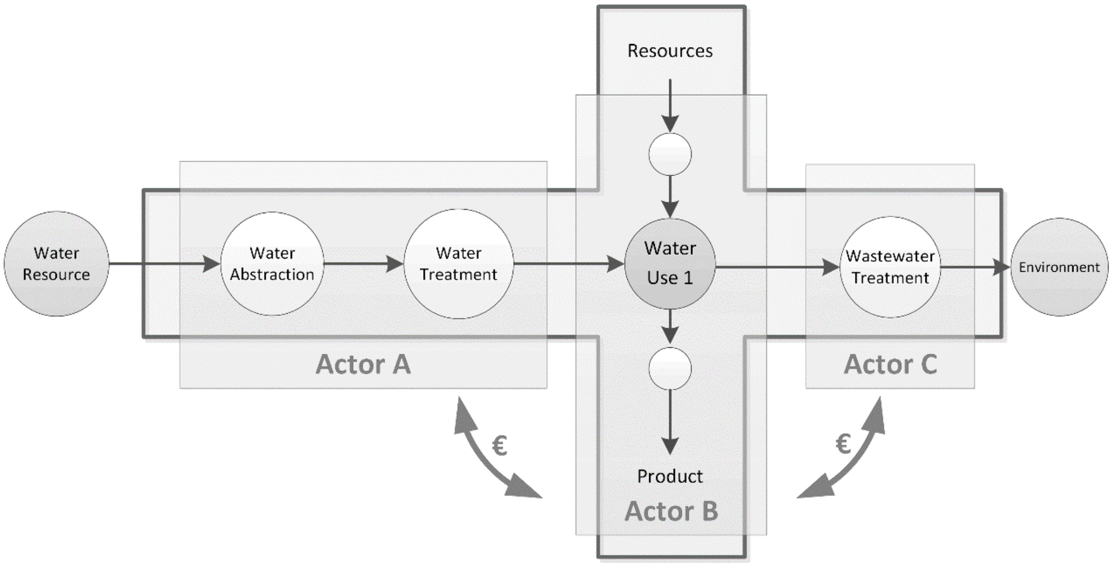

Figure 3. The meso-level water use system

3. MESO-LEVEL ECO-EFFICIENCY ASSESSMENT

Eco-efficiency has recently become an important concept of environmental decision making, serving both as a policy objective and as a measure of progress towards sustainability. It combines resource efficiency (the minimization of resources used in producing a unit of output) and resource productivity (the efficiency of economic activities in generating added value from the use of resources).

It was introduced as a term in the late 1980s and was first mentioned in scientific reports in 1989 (Schaltegger and Sturm, 1989). The first official definition belongs to the World Business Council for Sustainable Development which examined the economic welfare of a business but at the same time explored and assessed the ecological impact of its products (WBCSD, 2000). Following that, several definitions have been proposed (Huppes and Ishikawa, 2005), all of them focusing explicitly on a business level, aiming to support decision makers maximizing the business profit but at the same time reducing its environmental impact. Based on these definitions, several studies have been carried out, focusing on a company (Burritt and Schaltegger, 2001), business unit (Van Caneghem et al, 2010), or a specific product (Wall-Markowski et al., 2005; Michelsen et al., 2006).

A shift of the concept of eco-efficiency from the business level to wider and more diverse systems was attempted through the definition of OECD (1998), which expressed eco-efficiency as the ratio of the economic output of an entity (e.g. a firm, sector or the entire economy) to the environmental impact generated by the same entity during the production process. Several eco-efficiency assessment studies has been performed on various scales, focusing on the regional (Melanen et al., 2004; Mickwitz et al., 2006) and national level (Jollands et al., 2004; Wursthorn et al, 2011) or on a specific sector of economic development (Ingaramo et al, 2009; Koskela, 2015), and using various alternative methodologies (Avadi et al., 2014; Wang et al., 2015).

The main issue concerning existing eco-efficiency assessment frameworks is the lack of: (a) a common and homogenous approach which could be applied in different systems and (b) benchmarking values for the most widely used eco-efficiency indicators which would facilitate the comparison between different systems or alternative configurations of the same system. Recently a standardized process for the eco-efficiency assessment of a product system has been introduced (ISO, 2012), which however focuses only on the assessment of its environmental impacts. The aim of the present paper is to fill this gap by introducing a systemic approach, developed during the EcoWater project, for the eco-efficiency assessment of meso-level water use systems and the anticipated eco-efficiency improvement from the introduction of innovative technologies. In such an approach, water should be considered in three different ways:

- As a resource, which allows assessing the resource efficiency of the system;
- As a productive input, in order to estimate the total value added from water use to the final product; and
- As a waste stream, in order to assess the environmental impacts of water use and to identify potential synergies/alternative uses for these streams

One other novelty of the proposed approach is that, due to its systemic nature, it does not only assess the eco-efficiency of the whole system, but the performance of its components as well. More specifically, the environmental performance of all the stages and processes of the system is examined in order to identify the environmental hotspots, and subsequently the areas of potential interventions. Furthermore, the economic performance of each individual directly involved actor is monitored in order to identify those with a negative balance and asses potential trade-offs or other economic incentives which may improve the situation. Thus, such an approach allows to identify the factors that are influencing the eco-efficiency of the system, to better inform decision-making and to provide policy recommendations which could promote the uptake of eco-innovations (Levidow et al., 2015).

The developed methodological framework consists of four distinct steps. The first step provides a detailed mapping of the studied system and the respective value chain, while the second step provides the means to assess its eco-efficiency. The assessment of the environmental performance follows a life-cycle oriented approach using the midpoint impact categories (including the impact from the background systems). The economic performance of the water use system is measured using the Total Value Added to the product due to water use. Alternative innovative technologies are selected in the third step and assessed in the fourth and final step. The four steps of the proposed methodology as well as some preliminary conclusions drawn from its application are presented in the following sections.

3.1 System Framing

The mapping of the system under study includes the definition of its boundaries and its special characteristics as well as the functional unit. A generic system, which models the actual meso-level water use system. It is represented as a network of unit processes (Figure 4). Each process represents an activity, which implements one or more technologies, where materials are processed and converted into other materials, while emissions are released to the environment (air, land, water) or into the system water flow.

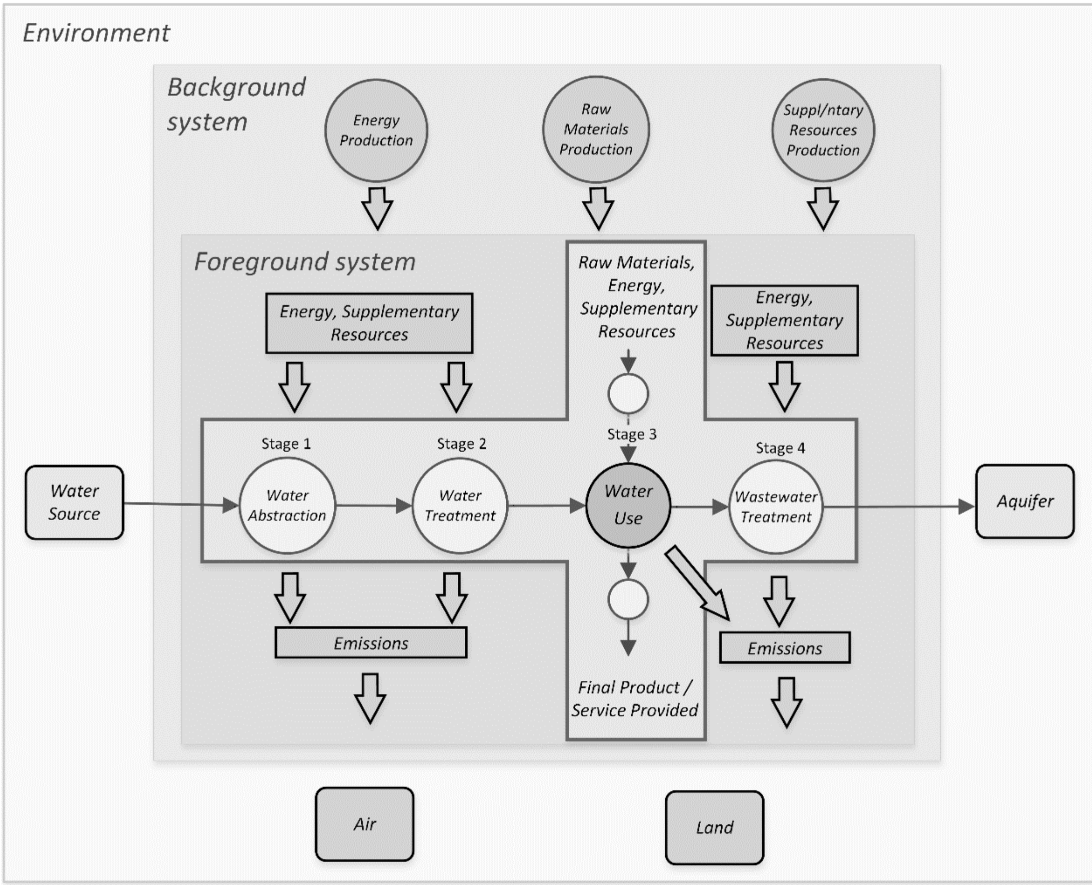

Figure 4. The generic meso-level water use system

A key characteristic element in a typical life cycle approach is the distinction between "foreground" and "background" systems:

- The set of processes whose selection or mode of operation is affected directly by decisions based on the study constitutes the foreground system.
- The background system includes all other activities and is that which delivers energy and materials to the foreground system, usually via a homogeneous market so that individual plants and operations normally cannot be identified.

As a general rule, case-specific primary data are used to describe the foreground processes, while more generic information is used for background processes (Guinée, et al., 2001). The boundaries of the foreground system encompass all the processes related to the water supply and the water use chains and can be grouped into four generic stages, presented in Table 1.

Finally, the functional unit is the foundation of a Life Cycle Assessment (LCA), because it sets the scale for comparison of two or more products or services delivered to the consumers (JRC, 2010; ISO, 2006). The main purpose of a functional unit is to provide a reference for normalization and comparison of results. Possible functional units for a meso-level water use system are:

- One unit of product or one unit of service delivered; and

- One unit (e.g. m^3) of water used.

Table 1. Generic stages in a meso-level water use system

No	Name	Description
1	Water Abstraction	Processes related to the abstraction of water from the environment and the distribution to the users
2	Water Treatment	Processes related the treatment of water according to the quality standards of the users
3	Water Use	Processes related to the production of goods or services
4	Wastewater Treatment	Processes related to the treatment of wastewater before disposing to the environment

3.2 Environmental Assessment

The evaluation of the environmental impacts follows the main stages of the typical LCA (Life Cycle Inventory Analysis and Life Cycle Impact Assessment) as described in ISO 14044 (ISO, 2006). Life cycle inventory (LCI) analysis involves creating an inventory of flows entering and leaving every process in the foreground system, i.e. the system within the defined system boundaries. Inventory flows include inputs and outputs of the generic “materials”, presented in Table 2.

In a typical LCA methodology, the inventory of flows must be related to the functional unit defined in the first step. However, in the proposed approach it is preferable to express the flows on an annual basis (e.g. m^3 of water abstracted per year, tons of product produced in one year), even if the functional unit is one unit of product or one m^3 of water used. This practice facilitates the calculation of annual costs and incomes during the value assessment phase. The environmental impacts per functional unit should be calculated by dividing with the corresponding elementary flow.

The Life Cycle Impact Assessment (LCIA) aims at evaluating the significance of potential environmental impacts based on the inventory of flows, and consists of the following elements:

- Selection of relevant impact categories;
- Classification and characterization; and
- Impact calculation.

Table 2. Material types in the meso-level water use system

Material Type	Description
Water	Water service related materials (fresh water, wastewater).
Resources	Various resources used in the processes of the water supply chain or in the production chain (energy, raw materials, chemicals, etc.)

Emissions	Emissions generated from the processes of both chains and released to the environment
Products/Services	The main outputs of the water use stage
By-products	Produced by the processes of both chains

Table 3. Midpoint impact categories

No	**Impact Category**	**Unit of measure**
1	Climate change	$tCO_{2,eq}$
2	Stratospheric ozone depletion	$kgCFC\text{-}11_{eq}$
3	Eutrophication	$kgPO_{4,eq}$ or $kgNO_{x,eq}$
4	Acidification	$kgSO_{2,eq}$
5	Human toxicity	$kg1,4DCB_{eq}$ or CTUh
6	Aquatic Ecotoxicity	$kg1,4DCB_{eq}$ or CTUe
7	Terrestrial Ecotoxicity	$kg1,4DCB_{eq}$ or CTUe
8	Respiratory inorganics	$kgPM_{10,eq}$
9	Ionizing radiation	kBq $U\text{-}235_{air,eq}$
10	Photochemical ozone formation	$kgC_2H_{4,eq}$
11	Minerals depletion	$kgSb_{eq}$ or $kgFe_{eq}$
12	Fossil fuels depletion	MJ or TOE
13	Freshwater depletion	m^3

The assessment of the environmental performance of the EcoWater water use system is implemented by using the midpoint impact categories presented in Table 3. This categorization makes it possible to characterize different environmental problems and cover all aspects of different impacts on human health, natural environment, and availability of resources. (Guinée, et al., 2001). They also provide a common basis for consistent and robust environmental performance analysis.

The purpose of classification is to organize and possibly combine the life cycle inventory flows into impact categories. The results, expressed as elementary flows, are assigned to impact categories according to the contribution of the resource/emission to different environmental problems. Characterization concerns the quantification of the extent to which each resource/emission contributes to different environmental impact categories and it is accomplished using standard characterization factors.

More specifically, the environmental impact for category c is expressed as a score (ES_c) in a unit common to all contributions within the category. The impact from the foreground processes can be easily calculated using the flows from the inventory analysis and the characterization factors, as follows:

$$(ES_c)_{fore} = \sum_r cf_{r,c} \times f_r + \sum_e cf_{e,c} \times f_e \quad (1)$$

where $cf_{r,c}$ the characterization factors of resource *r* for the impact category *c* (e.g. water for freshwater depletion, natural gas for fossil fuel depletion and phosphorus for mineral depletion); $cf_{e,c}$ the characterization factors of emission *e* for the impact category *c* (e.g. carbon dioxide for climate change, phosphorus for eutrophication and sulphur dioxide for acidification); f_r the elementary flow of resource *r*; and f_e the elementary flow of emission *e*. For example the climate change indicator ($ES_{climate}$) of a process which emits 1000 tonnes of carbon dioxide ($f_{CO2} = 1000\ t$), 10 tonnes of methane (f_{CH4} = 100 t) and 0.1 tonnes of nitrous oxide (f_{N2O} = 100 t) equals to:

$$ES_{climate} = cf_{CO2,climate} \times f_{CO2} + cf_{CH4,climate} \times f_{CH4} + cf_{N2O,climate} \times f_{N2O} \\ = 1 \times 1000 + 25 \times 10 + 300 \times 0.1 = 1280\ t_{CO2,eq} \quad (2)$$

where the characterization factors ($cf_{CO2,climate}$ = 1 $t_{CO2,eq}/t_{CO2}$, $cf_{CH4,climate}$ = 25 $t_{CO2,eq}/t_{CH4}$ and $cf_{N2O,climate}$ = 300 $t_{CO2,eq}/t_{N2O}$) have been retrieved from the CML-IA database (Guinee, et al., 2001).

On the contrary, the environmental impact from the background processes are evaluated based on secondary data, which is more generic and normally represent a mix or a set of mixes of different processes. Analysing the data provided by the LCA databases, environmental impact factors ($ef_{r,c}$), representing the environmental impacts from the production and/or transportation of one unit of a resource r to each impact category c, can be calculated. The contribution of background processes to the environmental impacts of category c is then calculated using these factors, as:

$$(ES_c)_{back} = \sum_r ef_{r,c} \times f_r \quad (3)$$

Background impacts are added to the foreground ones to calculate the system-wide environmental impacts.

$$ES_c = (ES_c)_{fore} + (ES_c)_{back} \quad (4)$$

3.3 Value Assessment

The selected economic performance indicator for the value assessment of a meso-level water use system, which takes into account the operation of both the water supply and the water use chains, is the Total Value Added (*TVA*) to the product due to water use, expressed in monetary units per period (i.e. €/year). It is estimated as:

$$TVA = EVU + VP_{BP} - TFC_{WS} - TFC_{WW} - TIC \quad (5)$$

where *EVU* is the total economic value from water use, VP_{BP} the income generated from any by-products of the system, TFC_{WS} the total financial cost related to water supply provision for rendering the water suitable for the specific use purpose, TFC_{WW} the total financial cost related to wastewater treatment and *TIC* the annual equivalent future cash flow generated from the introduction of new technologies in the system.

EVU refers to the total benefits from direct use of water. The approach followed for its estimation depends on whether the water is used as a resource in a production process (e.g. water use in industrial and agricultural sectors), or delivers a service to the customers (e.g. water use in urban sector).

In the first case, *EVU* is estimated using the residual value approach:

$$EVU = TVP - EXP_{NW} \tag{6}$$

where *TVP* is the Total Value of Products, and EXP_{NW} are the Non-Water Expenses, representing the expenses for all the non-water inputs, the fixed and variable operation and maintenance costs, the labour costs as well as the costs related to emissions in the water use stage (stage 3). They are estimated as follows:

$$TVP = \sum_p f_p \times p_p \tag{7}$$

$$EXP_{NW} = \sum_r f_{r,3} \times c_r + \sum_e f_{e,3} \times c_e \tag{8}$$

where f_p represents the production of product *p* at the water use stage, p_p is the unit price of product *p* and c_r, c_e the unit cost of resource *r* and emission *e* respectively.

The above approach cannot be applied to an urban water supply system, because the product is actually the service provided to households and to non-domestic consumers. Two alternative approaches could be used instead; either the customers' willingness to pay or the water supply cost. The customers' willingness to pay accounts for the water services provided and is defined as the maximum amount a person would be willing to pay in order to receive a reliable and adequate water supply. The water supply cost is determined by the processes required to abstract, treat and distribute water from the water utility company to the consumers. Their main difference is that the services provided (and subsequently the willingness to pay) do not change as a result of technology implementation for the upgrade of the entire value chain (i.e. the application of a technology or management practice will not result in supply interruptions or render the quality of water unsuitable for the specific purpose) whereas the supply cost can be affected by upstream technologies. In the proposed approach case, the measure that will be used to calculate EVU should be constant among the different scenarios in order to facilitate the comparison of the technologies' performance. For that reason, the willingness to pay is selected and based on the assumption that the total utility (the overall satisfaction of wants and needs) does not change between scenarios, the economic value from water use can be estimated by:

$$EVU = WTP \times f_{w,2-3}^{bl} \tag{9}$$

where *WTP* is the consumers' willingness to pay for the services provided (defined as the maximum amount a consumer would be willing to pay in order to receive a reliable and adequate water supply) and $f_{w,2-3}^{bl}$ is the total quantity of water supplied to the processes of water use stage in the baseline case, as denoted by the superscript *bl*.

TFC_{WS} represents the expenses in the processes of water abstraction and water treatment stages (stages 1 and 2):

$$TFC_{WS} = \left(\sum_r f_{r,1} \times c_r + \sum_e f_{e,1} \times c_e\right) + \left(\sum_r f_{r,2} \times c_r + \sum_e f_{e,2} \times c_e\right) \tag{10}$$

TFC_{WW} represents the expenses in the processes of wastewater treatment stage (stage 4):

$$TFC_{WW} = \sum_r f_{r,4} \times c_r + \sum_e f_{e,4} \times c_e \quad (11)$$

The *TVA* can be also calculated by aggregating the Net Economic Output (*NEO*) of all the actors directly involved in the system. The *NEO* is estimated by the following equation:

$$NEO_i = WS_i + VP_i - FC_i - IC_i \quad (12)$$

where WS_i represents the net revenues of the actor from the water services (incomes from services provided to other actors minus expenses for services received by other actors), while VP_i, FC_i and IC_i are the value of product(s), financial costs and annual investment costs, respectively, incurred in the pertinent stages of actor.

3.4 Eco-efficiency quantification

The Eco-Efficiency Indicators (*EEI*) of the meso-level water use systems are defined as ratios of the economic performance (expressed by the Total Value Added) to the environmental performance of the system (expressed through the environmental score for each one of the LCA midpoint indicators). It should be noted that the subcategories related to Ecotoxicity and Resource Depletion are considered separately, because they are expressed in different unit of measurement and cannot be aggregated. Thus, there can be 13 eco-efficiency indicators for each studied system, one for each environmental impact category c, and can be calculated as follows:

$$EEI_c = TVA / ES_c \quad (13)$$

3.5 Special methodological issues

This section addresses two special methodological issues regarding: a) the handling of “recovered resources” (e.g. energy, phosphorus, etc.), generated due to the implementation of innovative technologies and b) the assessment of environmental impacts from freshwater use.

3.5.1 Recovered Resources

Recovered resources, as a result of applying an innovative technology, will affect the eco-efficiency of the water system and should be included in the analysis. The problem is more complex when the recovered resources are exported and used outside of the system boundaries. In a typical LCA analysis, this problem is handled by an expansion and substitution approach.

According to JRC (2010), when a process of a system provides more than one function, i.e. delivers several goods and/or services, it is defined as multifunctional. Multifunctionality in the analyzed meso-level water use systems occurs due to the introduction of innovative technologies, as for example in the following cases:

- Introduction of a hydropower generator in an urban water supply network, which functions as a pressure reduction valve, and at the same generates

electricity which can be used on-site, exported to the grid or stored for future usage.
- Introduction of advanced phosphorus recovery technologies in the processes of the wastewater treatment stage. The recovered phosphorus can be sold for use to another system.

The environmental impacts of these multifunctional processes are handled as follows:

- In case of on-site use of the generated resource (closed-loop recycling) the consumption of primary resources is reduced, thus improving the environmental performance of the system; hence the amount of the recovered resources will be subtracted from the relevant elementary flow during the environmental impact assessment. The economic performance of the system is affected as well, as the costs related to resource used and the additional technology is considered for the estimation of the TVA.
- When the recovered resources are exported to another system (open-loop recycling) the economic and the environmental performance of the analyzed system are affected as follows:
    - The cash flow from the sale of the recovered resources will be considered for the estimation of the TVA produced, as a benefit of the relevant actor due to technology uptake.
    - The reduced amount of resources in the wastewater stream will mitigate relevant environmental impacts. The potential environmental benefits associated with the use of recovered resources (e.g. reduced amount of primary materials and energy sources) will not be considered, as they are ascribed to the system where the use of resources takes place.

3.5.2 Freshwater Resource Depletion

Impacts from the use of freshwater (resource depletion) are far from being standardized in current LCIA practice (Muñoz, et al., 2010). It has been suggested by practitioners that water depletion should be treated as a separate issue (and not assessed in an overall resource depletion impact category), due to its regional dependence and to the fact that it is only temporarily removed from circulation but may be discharged on a different water body, that make the problem of water availability very different from the other natural resources. However, no characterization factors are proposed for its assessment (JRC, 2011).

To date, most studies have neglected this issue or treated it as a simple indicator, expressing the volume of abstracted water by the product system (Muñoz, et al., 2008). However, in the case of water use systems, freshwater resource depletion cannot be neglected. In the proposed approach, the methodology presented by Mila i Canals (2009) and suggested by JRC (2011) is used. It is based on the Freshwater Ecosystem Impact (*FEI*) indicator, which addresses the potential effects on aquatic ecosystems caused by changes in freshwater availability due to abstraction, and is defined as:

$$FEI = f_{w,0-1} \times WTA \quad (14)$$

where $f_{w,0-1}$ is the freshwater abstracted and *WTA* is the water withdrawal to availability ratio. The latter can be defined as:

$$WTA = WU/WR \tag{15}$$

where *WU* is the total annual freshwater withdrawal in a river basin and *WR* represents the annual freshwater availability in the same basin.

One of the main issues that have not been resolved yet is whether non-evaporative use of water should be included in the assessment. Although non-evaporative use of water has minimal impact on the water balance on a global scale, its non-inclusion may lead to an underestimation of the local effects of water abstraction (e.g. when groundwater is abstracted or when the discharged water returns to a different water body than the water source) (Mila i Canals, 2009). Thus, in order to develop a common approach for all the case studies, both evaporative and non-evaporative water uses are included in the analysis.

3.6. Selection of Innovative Technologies

A water use system can be upgraded through one or more of the following alternative ways (Humphrey & Schmitz, 2000):

- Process upgrading, which will result in a more efficient transformation of the inputs into outputs, by rearranging the production line, by introducing new technologies or by recycling/reusing the generated wastewater/effluents;
- Product upgrading, by changing to a more profitable product line (i.e. a product with higher economic value); and
- Functional upgrading, by acquiring new functions in the value chain (i.e. marketing).

In the proposed approach, the focus is on process or product upgrading, by introducing technologies which reduce the overall environmental impact or improve the quality/quantity of the final product.

A preliminary selection of innovative technologies is formulated based on the existing lists of Best Available Techniques for each sector and the relevant literature. The final selection is guided by the eco-efficiency assessment of the system in its current state ("baseline scenario"), and the identification of its vulnerabilities and environmentally weak stages. More specifically, the breakdown analysis of environmental and eco-efficiency indicators per stage and the estimation of the foreground and background system contribution reveal potential areas for improvement through the implementation of new technologies. These can be classified according to the stage at which they are implemented (Figure 5):

- Technologies in the water supply chain (common in all water use systems); implemented either upstream (e.g. water treatment) or downstream (e.g. wastewater treatment) of the water use stage; and
- Technologies in the production chain (sector specific).

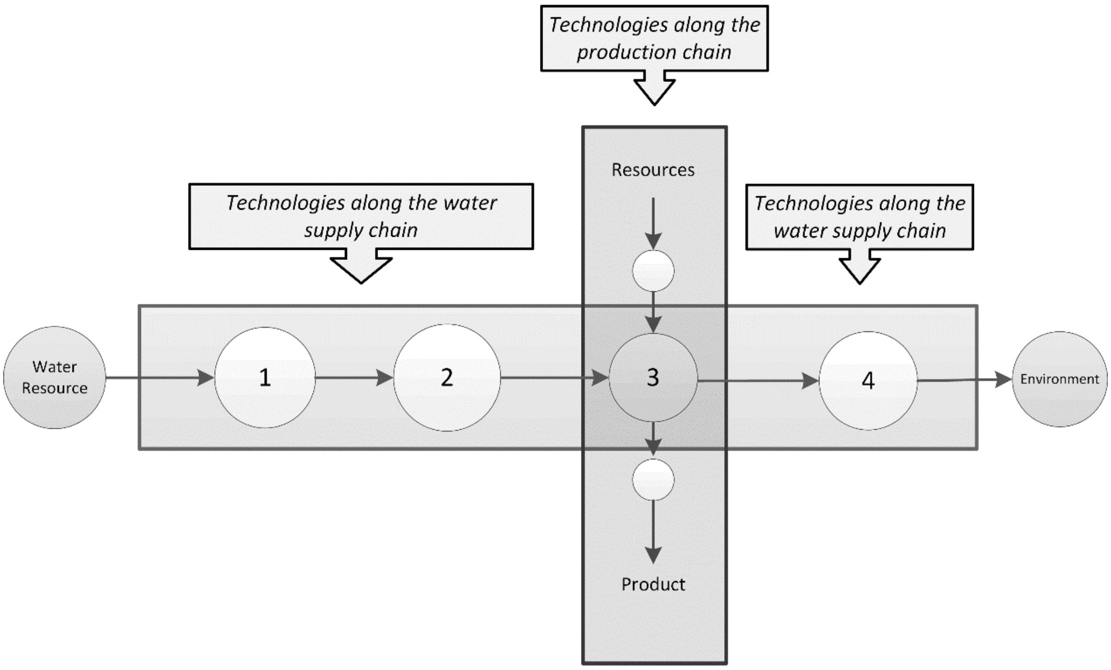

Figure 5. Innovative technologies implementation in different stages of water system

The technologies can be also classified in three categories according to the objective of their implementation:

- Resource efficient technologies, focusing on water, energy or material savings;
- Pollution preventing technologies, aiming to reduce the emissions to air, to water and to soil; and
- Technologies enhancing circular economy, such as reuse, recycle or recovery.

3.7. Technology Scenarios

For the purposes of the developed framework, a technology scenario can be defined as "the implementation of (at least) one innovative technology in the system under study, assuming that all other parameters remain the same". The first step is the screening of all available technologies through an individual eco-efficiency assessment. The eco-efficient ones are identified and then ranked based on their performance towards the three key objectives: (a) Pollution Prevention, (b) Resource Efficiency and (c) Circular Economy. According to the individual assessment of technologies, alternative technology scenarios are formulated, focusing on each of the three key objectives and including all the relevant eco-efficient technological options. For each technology scenario, the distributional issues among the actors are analyzed, in order to examine their feasibility:

- If the TVA of the system and the NEO of all actors increases, then the scenario is feasible and can be implemented
- If the NEO of certain actors decreases (especially if the affected actors are the ones who will implement the technology), then additional policies are required for managing the distributional issues

4. APPLICATION OF THE PROPOSED FRAMEWORK

The proposed methodological framework has been successfully tested in eight case studies, formulated around a unifying theme (water use in agriculture, urban and industrial systems). The simulation and the assessment of all case studies was performed using the EcoWater Toolbox, an integrated suite of on-line tools and resources for assessing eco-efficiency improvements from the implementation of innovative technologies in water use systems, and a pair of modelling tools, the "Systemic Environmental Analysis Tool" (SEAT) and the Economic Value chain Analysis Tool" (EVAT), which combines both economic and environmental viewpoints into a single modelling framework (Arampatzis et al, 2014). The characterization factors for the foreground system, included in the indicators inventory of the Toolbox, are extracted from the CML-IA database (Guinee, et al., 2001). The background environmental impacts are evaluated using data from several open access LCA databases (ELCD, 2013; USLCI, 2012) which contain inventory data of many basic materials, energy carriers, waste management and transport services.

The eight EcoWater Case Studies include:

- Two agricultural water use systems, the irrigation schemes of Sinistra Ofanto, Italy and Monte Novo, Portugal, which focus on shifts from rainfed to irrigated agriculture and innovations that can reduce the relevant water and energy footprints and production inputs.
- Two water supply systems of the cities of Zurich, Switzerland, and Sofia, Bulgaria, which have addressed issues and technologies associated with more sustainable and economically efficient urban water management, water conservation practices and cleaner production technologies in households.
- Four industrial water use systems, focusing on the textile, dairy and automotive industries and the cogeneration of thermal energy and electricity. Emphasis is placed on the assessment of technologies towards closed-loop systems, recovery of resources and advanced water and wastewater treatment, and on the economic impacts among the actors involved.

4.1 Baseline Eco-efficiency Assessment

The results of the baseline eco-efficiency assessment are presented in Table 4. The cross-comparison of these case studies leads to the identification of potential areas of improvement by highlighting the weak stages in the water supply chain of each case study and by comparing similar stages/processes across case studies.

Table 4. General Characteristics of EcoWater Case Studies

Case Study	Location	Main Characteristics	Product/Service	Water Abstracted (annually)
CS#1. Sinistra Ofanto Irrigation Scheme	Apulia Region, Italy	Old system (founded in the 1980s) with water scarcity issues and total irrigated area of 28,165 ha.	Grapes (370,000t), Olives (28,000 t) and Orchards (80,000t)	36.5 Mm^3 Surface Water and 62.5 Mm^3 Groundwater
CS#2. Monte Novo Irrigation Scheme	Alentejo region, Portugal	New system (began operating in 2009) with subsidized water prices until 2017 and a total irrigated area of 7,800 ha.	Maize (20,000 t), Olives (18,000 t) and Pastures (5,000 t)	21 Mm^3 Surface Water
CS#3. Sofia Urban Water Supply System	Sofia, Bulgaria	Old (more than 100 years old) and inefficient system with significant water losses (~50%) in the water distribution network.	Provides water to 1.2 million inhabitants	206,2 Mm^3 Surface Water
CS#4. Waedenswil Urban Water Supply System	Zurich, Switzerland	New and modern water supply (rebuilt in 2012) with technologically advanced wastewater treatment plant.	Provides water to 20,000 inhabitants	2.5 Mm^3 Surface and Groundwater
CS#5. Textile Industry	Biella , Italy	Two representative SMEs (out of 650) are examined focusing on the dyeing process and the differences between chemical and natural dyeing.	890 t chemically dyed wool and 100 t naturally dyed wool	0.95 Mm^3 Surface Water and 0.75 Mm^3 Groundwater
CS#6. Energy Industry	Amsterdam, Netherlands	The examined plant operates from the mid-1990s with an installed capacity of approximately 250MWe and 180MWth.	Provides electricity to >300,000 and district heat to 90,000 households	65 Mm^3 Surface Water (for Cooling)
CS#7. Dairy Industry	Holstebro, Denmark	Environmental friendly dairy industry focusing on water reuse and recycling technologies.	17,000 t milk powder	0.53 Mm^3 Groundwater
CS#8. Automotive Industry	Umeå and Gothenburg, Sweden	Two separate water value chains are examined with a high value final product (100,000€ per cabin)	30,000 truck cabins	0.41 Mm^3 Surface Water

The comparison of the two agricultural case studies leads to the conclusion that the main environmental hotspots in both cases are (a) freshwater resource depletion due to excessive depletion of aquifers, (b) climate change impact due to direct emissions from fertilizer and fuel consumption and (c) eutrophication of groundwater and surface water due to NO_3^- and PO_4^{3-} leaching. However, CS#1 irrigation scheme has a better eco-efficiency performance than the CS#2 irrigation scheme, mainly because the latter is characterized by increased fuel consumption for pumping.

Table 5. Baseline eco-efficiency assessment results

Indicators	Agricultural		Urban		Industrial			
	CS#1	CS#2	CS#3	CS#4	CS#5	CS#6	CS#7	CS#8
Climate Change (€/$tCO_{2,eq}$)	1081	186	94	373	1351	0.12	30.1	44000
Stratospheric Ozone Depletion (€/$kgCFC11_{eq}$)	NR*	NR	>10^6	>10^6	NR	NR	NR	>10^6
Eutrophication (€/$kgPO^{-3}_{4,eq}$)	109	15.4	41.7	4.9	1025	NR	0.99	42000
Acidification (€/$kgSO_{2,eq}$)	82.6	21.8	4.4	215	366	37.8	3.1	15000
Human Toxicity (€/$kg1,4DCB_{eq}$)	19.9	1.7	1.1	4.5	6.8	7.2	28.5	2000
Aquatic Ecotoxicity (€/$kg1,4DCB_{eq}$)	74.5	10.9	13.3	15.6	0.8	13325	737	1800
Terrestrial Ecotoxicity (€/$kg1,4DCB_{eq}$)	3866	106	513	6000	9.5	191	630	>10^6
Photochemical Ozone Formation (€/$kgC_2H_{4,eq}$)	8417	518	111	8822	6959	610	3271	>10^6
Respiratory Inorganics (€/$kgPM_{10,eq}$)	3007	143	22.5	1257	NR	31590	NR	NR
Minerals Depletion (€/$kgFe_{eq}$)	7948	923	42.4	NR	NR	NR	NR	NR
Fossil Fuels Depletion (€/MJ)	4.9	0.007	0.01	0.03	NR	0.01	NR	NR
Freshwater Depletion (€/m^3)	7.0	0.6	1.1	31.6	122	13.5	203	17000

* The indicator is characterized as non-relevant to the Case Study since there are no related elementary flows to the corresponding inventory

Similar conclusions may be drawn by examining the two urban case studies. Both case studies have common environmental hotspots; freshwater resource depletion, climate change impact and fossil fuel depletion. However, each system has also its own characteristics which require monitoring through the indicators (sludge transportation for Sofia / micropollutants emissions for Zurich). When comparing their eco-efficiency, it is obvious that the urban water supply system of CS#3 has a worse performance, due to two main reasons: (a) the infrastructure is older, leading to an increased amount of water leakages, (b) the households use an extensive amount of water, resulting to a much lower eco-efficiency value for the freshwater depletion indicator, and (c) the energy mix for electricity production in CS#3 is less environmental friendly, with a very small share of renewable energy sources, compared to CS#4. Finally, the TVA for Zurich is four times higher than for Sofia, reflecting their wider difference in their economic situation and GDP per capita.

A direct cross-case comparison is not so meaningful for the industrial Case studies since the production lines differ a lot and the main conclusions are mostly case (or sector) specific. Thus, a straightforward decision regarding the best eco-efficiency performance among the 4 industrial Case Studies cannot be made. However, it is still possible to identify the main environmental weakness of each system. The major environmental impact of the textile industry (CS#5) concerns aquatic and terrestrial ecotoxicity, due to the chemicals used in the dyeing process and the related pollutants in the effluents (e.g. heavy metals, BOD, COD). The corresponding indicator is at least 10 times lower than in any other case study. Furthermore, compared to the other industrial cases, the textile industry uses large amounts of freshwater (mainly during wet processing operations, such as dyeing and finishing). As expected, the energy industry (CS#6) has the worst performance among all case studies concerning the climate change indicator and one of the lowest concerning fossil fuels depletion, due to the high consumption of natural gas and the related emissions to air (both greenhouse gases and toxic substances). However, the analysis also revealed that one of the most important environmental weaknesses of the system is the increased thermal pollution due to large amounts of waste heat rejected to the surface water through cooling water. The proposed set of common indicators does not include an appropriate indicators, and for the purposes of the analysis the total amount of waste heat is used a proxy indicator. The most important environmental issue related to the operation of the dairy industry (CS#7) is eutrophication, due to high amounts of BOD, COD and organic residues released to the environment. Moreover, the climate change impact indicator is relatively low, primarily due to the background impact from energy use for process heating and circulation pumps. The environmental hotspots of the automotive industry are eutrophication, due to the phosphorus in wastewater, aquatic ecotoxicity, due to the heavy metals in wastewater after the corrosion protection process, and climate change, due to the background impact of energy production, which is then used for process heating and circulation pumps. However, the values of the eco-efficiency indicators for the automotive industry (CS#8) are of a different order of magnitude due to the increased value of the final product (compared to all the other 7 products), which significantly affects the TVA of the system.

4.2 Assessment of Technology Scenarios

Three alternative scenarios are formulated for each case study, consisting of technologies implemented in both the water supply chain and the production chain. All the examined technologies are presented in Table 6 whereas a more detailed description can be found in the EcoWater Toolbox technology inventory (Arampatzis et al, 2014). The water supply chain technologies are implemented in all the case studies, provided that they are applicable to the system (i.e. a wastewater treatment technology cannot be applied in an agricultural system).

Table 6. List of water supply chain and production chain technologies and the objective of their implementation: (PP: Pollution Prevention, RE: Resource Efficiency, CE: Circular Economy)

Water Abstraction and Distribution	Variable speed pumps (PP) Pressure Reduction Turbines (RE, CE) Smart Pumping (RE) Solar Pumping (PP)
Water Treatment	Membrane distillation (PP)
Wastewater Treatment	Micropollutants Removal (PP) Advanced Phosphorus Recovery (PP, CE) Solar Drying of Sludge (PP, CE) Advanced Oxidation Processes (PP) Anaerobic pre-treatment of wastewater (PP) Membrane Bioreactor (PP)
Agricultural Water Use Systems	Regulated Deficit irrigation (RE) Organic Fertilizers (PP) Drip and Sub-surface drip irrigation (RE)
Urban Water Supply Systems	Solar water heating (PP) Domestic water saving appliances (RE) Drain water heat recovery (PP)
Textile Industry	Use of natural dyes (PP) Automatic dye and chemical dispensing (RE) Low-liquor-ratio jet dyeing machines (RE)
Energy Production Industry	Heat-only boilers (RE, PP) Thermal energy buffer (RE, PP) Micro-CHP (RE, PP) Potable water preheating (CE)
Dairy Industry	Product and water recovery from CIP (RE, PP) Cleaning and reuse of condensate (RE, CE) Anaerobic digester (PP) Advanced oxidation and UV (PP, CE)
Automotive Industry	Silane-based metal surface treatment (RE) Recycling of process water and chemicals (RE, PP, CE)

Table 7 summarizes the improvements in the environmental performance of the water use systems, under three alternative scenarios, concerning the implementation of innovative technologies of the three categories (resource efficient, pollution prevention and circular economy) as presented in sections 3.6 and 3.7. Specifically, the reduction in water and energy use are shown, expressing the range of potential improvements in each case study. A negative value implies an overall improvement, since the respective impact is reduced. In addition, Table 8 presents the changes in net economic output of the main involved actors under the same three technological scenarios, expressing the distributional issues, as discussed in section 3.7.

The two agricultural systems have an identical behavior. There is room for improvement concerning pollution prevention in both cases and the corresponding technologies can be more easily implemented since all actors have a positive net economic output. On the contrary, when implementing water saving technologies (resource efficiency scenario), the farmers are losing money, although the overall eco-efficiency is improving. In this case, additional economic incentives (e.g. subsidies, tax exemption) should be considered in order to promote their uptake.

The two urban water supply systems have also a similar behavior and exhibit a significant potential for improving the environmental hotspots; especially CS#3 which has the worst baseline performance. Domestic water users improve their economic performance in most cases, even when they are the stakeholder responsible for the installation of water saving appliances in the households. However, water utility and wastewater treatment companies demonstrate economic losses in most of the scenarios, which could potentially lead to an increase of the water or wastewater rate. This will have a positive impact on the net economic output of the companies and will not affect the overall eco-efficiency, but will deteriorate the economic performance of the consumers. Thus, in order to maintain the economic viability of such a scenario, alternative policy instruments targeting the water consumers should be taken into consideration to counterbalance this effect. It should be also mentioned that the pollution prevention scenario for CS#4 is not economically favorable, because two of the actors have a negative economic performance. However, it is a scenario that will be probably implemented due to recent more strict national legislation on micropollutants removal. This example can be used to highlight the fact that stringent environmental regulations can be an effective driver for promoting eco-innovative technologies.

Table 7. Environmental performance improvement potential for the three scenarios

Case Study	**Resource efficiency scenario**		**Pollution prevention scenario**		**Circular economy scenario**	
	Water Use	**Energy Use**	**Water Use**	**Energy Use**	**Water Use**	**Energy Use**
CS#1	-6.3%	-5.9%	0%	-9%	No Scenario	
CS#2	-8.7%	-8.3%	0%	-5%	No Scenario	
CS#3	-9.0%	-8.0%	-9%	-14%	0%	-1%
CS#4	-13%	-6%	-1%	0%	-2%	0%
CS#5	-52%	-15%	0%	-0.8%	No Scenario	
CS#6	No Scenario*		-18%‡	-11%	-30%*	+1%
CS#7	-47%	0%	-133%	0%	-316%	0%
CS#8	-1.1%	-2.8%	-1.5%	+3.9%	-1.3%	+4.4%

* "No Scenario" indicates that the scenario has not been applied to the corresponding Case Study (mainly because of the lack of relevant technologies).

‡ CS#6: In Water Use column the Thermal Pollution Reduction in the receiving water body is shown.

Industrial water use systems are in a more technologically advanced level concerning the reduction of air emissions (due to the already established European and national regulations) and the potential for improvement is relatively low. Thus, pollution prevention scenarios are mainly focused on reducing pollutants in water effluents. Concerning resource efficiency, water savings potential in the industrial case studies is high. Dairy and textiles industry demonstrate the highest potential among all eight examined systems, which can reach 50%, by introducing technological measures to exploit water extracted from milk and by replacing traditional dyeing processes with innovative options utilizing less water, respectively.

Table 8. Net Economic Output change for the main involved actors

Case Study	Resource efficiency scenario			Pollution prevention scenario			Circular economy scenario		
	Water Utility	**Water User**	**WW Utility**	**Water Utility**	**Water User**	**WW Utility**	**Water Utility**	**Water User**	**WW Utility**
CS#1	0%	-3.1%‡	N/A*	0%	+1.2%	N/A	No Scenario		
CS#2	+6%	-7.5%	N/A	0%	+11%	N/A	No Scenario		
CS#3	-21%§	+13%	-21%	-20%	+10%	-20%	+9%	0%	+9%
CS#4	-1%	+19%	-17%	0%	-2%	-48%	0%	-3%	0%
CS#5	0%	+11%‡	0%	0%	-6.8%	+6.7%	No Scenario		
CS#6	No Scenario‡			0%	+11%	0%†	0%	+9%	-11%
CS#7	-55%	+10%	-42%	-26%	+10%	-6%	-75%	+10%	-41%
CS#8	0%	+0.3%	-57%	-12%	+0.3%	-57%	-12%	+0.2%	0%

* N/A indicates that there is no relevant actor for the corresponding Case Study, whereas “No Scenario” indicates that the scenario has not been applied to the corresponding Case Study (mainly because of the lack of relevant technologies).

‡ In CS#1 and CS#5 there is more than one water user. The worst economic performance is shown.

§ In CS#3, water utility and wastewater utility are managed by the same actor.

† In CS#6, the NEO of the end-users of electricity and thermal energy is presented in the 3rd column instead of WW Utility.

As it is expected, the water user is, in all four cases, the actor responsible for applying the majority of eco-innovations. This means that a high investment cost is required by the industry and its economic performance becomes a critical factor in the final decision. More specifically, for the textile industry, the high investment is a prohibitory factor on its own, due to the current local economic conditions and the ongoing economic crisis which has significantly affected the regional economy, whereas in the case of the automotive industry, the anticipated profit is marginal and insignificant compared to the overall capital required. In both cases, further economic incentives (e.g. tax exemption, green certificates) are required to motivate the industrial actor to invest in environmentally friendly technologies. In the case of textiles, the joint implementation of a technology, together with other neighbouring industries, was considered as a potential solution. Moreover, the industrial stakeholders in all four case studies have agreed that the implementation of eco-innovations in the industrial sector can be more easily promoted if the technologies are included in the corresponding Best Available Techniques (BAT) Reference Documents (the so-called BREFs).

Concerning scenarios towards circular economy, very few potential synergies were identified in the urban and agricultural water use systems, since there are less available waste streams that could be used as an input to another system. Thus, no scenarios were assessed for the agricultural systems whereas the scenarios examined for the urban systems have minor impact at the system. More opportunities were identified in the industrial water use systems, however they were mainly focused on internal reuse of the recovered waste stream inside the boundaries of the system. A more detailed cross comparison of the EcoWater Case Studies can be found in EcoWater (2015).

5. CONCLUSIONS

Based on the application of the methodological framework for the purposes of the EcoWater Project, it can be said that the proposed systemic approach provides a concrete, comprehensive economic and environmental performance assessment of a water use system and of all directly involved actors. The results are more accurate when the approach is used for the comparison of two different systems with a similar product or two (or more) alternative configurations of the same system.

Furthermore, its application in eight different water use systems and the cross-comparison of the results has led to:

- Definition of a range for each indicator and reference values for normalizing them;
- Technology benchmarking for a specific sector by providing a reference value for eco-efficiency improvements; and
- Identification of the most eco-efficient technological options in each case study.

The application of the proposed methodological framework can lead to better informed decision making towards the improvement of the environmental and economic performance of a given system. By comparing its environmental performance to a similar one that has been already assessed, the weak stages in the water supply chain are highlighted, the potential areas of improvement are acknowledged and the appropriate technological interventions are selected from the inventory. Through the economic performance assessment of each actor separately, the actors who will be negatively affected by the implementation of the suggested technologies are identified. Such information can be very helpful for prioritizing and targeting policy actions. Economic incentives (e.g. subsidies, tax exemptions) could be considered, for example, when the objective is to increase the NEO of a specific actor/sector without affecting the others. Alternatively, the legal framework for promoting industrial cooperation (for joint technology implementation) or public private partnerships could be identified as the appropriate action when the objective is to increase the NEO of a specific actor and decrease the NEO of another actor, in order better distribute among the value chain the investment cost of the new technologies.

However, the wide application of the proposed approach has also revealed its weaknesses as well as areas for further research. Environmental impacts were evaluated following a Life Cycle Analysis, using indicators for midpoint impact categories. However, the existing set of categories and the corresponding indicators is not sufficient. The most important gap concerns freshwater depletion which plays a significant role in all examined case studies. The Freshwater Ecosystem Impact indicator, which was used by including both evaporative and non-evaporative, gave misleading results in cases where there no evaporative water uses and water was discharged in the same water body (CS#4 and #6). Moreover, additional indicators needed to be introduced in order to assess case-specific environmental impacts, due to the nature of the system (thermal pollution in water due to rejected heat – CS#6) or due to regional environmental targets (reduction of micropollutants in the water - CS#4). Economic performance was assessed using the Total Value Added to the product from water use. The willingness-to-pay approach was used in the cases of urban water supply (when the product is the service provided to domestic and non-domestic consumers). The main open methodological issue is the suitability of the TVA (as defined for the purposes of this project) as the appropriate metric for assessing the economic performance of industrial water use systems. Due to the very diverse production lines and the differences in the value of the final product, the range of values for the TVA is very large and affects significantly the eco-efficiency results.

In order to overcome these difficulties, a more homogenous approach should be established for all sectors concerning not only the foreground system boundaries but also the background processes. Moreover, the number of case studies examined should be increased in order to validate reference values for the eco-efficiency indicators. This will help clarify if and how can the results from the cross-comparison among Case Studies from different sectors be meaningful for system a cross-sectoral technology benchmarking.

Finally, another key issue is to define the most important transition factors in enabling effective change towards systemic eco-efficiency improvement. To this end, the current methodological framework (both the approach proposed and the indicators list) could be upgraded from linear to circular modeling, in order to be able to assess the performance of an eco-industrial park. This will facilitate the transition to a more circular economy by integrating production chains through environmental partnerships and by promoting industrial symbiosis.

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Highlights for Paper JCLEPRO-D-15-00979. Systemic eco-efficiency assessment of meso-level water use systems

- An approach has been developed to assess the eco-efficiency of a water use system
- It has been applied in 8 case studies formulated around a unifying theme; water use
- The opportunities for eco-efficiency improvement in each system have been discussed
- The distributional issues among the actors of the value chain have been assessed
- This systemic approach can lead to better informed decision and policy making