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Sustainability criteria for the selection of water supply pipeline

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Abstract: The evolution of the materials used for drinking water pipelines has often introduced substantial innovations in the market, both in terms of improved static and hydraulic performance and cost. Over time, technical and cost-effective assessments to pipelines selection, related to the materials used, have been accompanied by environmental assessments in relation to the environmental impact of construction and management of drinking water system. The recent legislative and technical regulations have made the environmental cost assessment more complex, which is related to the life cycle of materials and infrastructures. This paper proposes an index, *In Situ* Sustainability Index (ISSI), which can be used for the pipelines materials choice for drinking water systems and which takes into account both technical and environmental aspects. This index considers the interaction between piping and laying soil, through the *In Situ* Elasticity Coefficient and the impacts of materials used for water system piping through Life Cycle Assessment. The ISSI index is a practical tool because it makes a simultaneous consideration of two essential aspects in the design (technical and environmental evaluations) through a rapid-use analytical structure.

Subjects: Environmental Management; Environment & Resources; Environmental Change & Pollution

Keywords: sustainable water management; environmental impacts; life cycle assessment; pipe materials; pipe/soil interaction; sustainability criteria

ABOUT THE AUTHOR

The DIATIC research group deals with Sustainable Water Management with specific reference to hydraulic mathematical modeling, to quantify the physical and hydraulic aspects that have an impact on the operational management of infrastructures. Mario Maiolo is coordinator of Italian Regional Project (POR CALABRIA FESR 2014-2020)—Innovation and Competitiveness (I&C)—project: “origAMI—original Advanced Metering Infrastructure. Daniela Pantusa received the degree in Civil Engineering in 2002 and her Ph.D degree in 2007 from University of Calabria. She is currently Research Associate at the Department of Innovation Engineering, University of Salento. Her research activity is mainly focused on sustainable management of water resources, drinking water supply systems, optimization of water resource management, hydraulic and maritime engineering.

PUBLIC INTEREST STATEMENT

Today on the market there are a various types of drinking water pipes which are distinguished by technical characteristics and material type. Normally the pipe choice is made on the basis of technical information. The aim of this research is to define a synthetic index useful to support the choices of the drinking water pipelines materials that takes into account technical but also environmental aspects. In particular, the proposed index considers two parameters, one of which depends on the pipes and soil characteristics and the other one regards the pipes life cycle environmental impacts.

1. Introduction

In the recent years, the Commission and the European Parliament have paid particular attention to the correct and sustainable water management through the Water Framework Directive (European Union 2000/60), the WISE project (Water Information for Europe), the INSPIRE Directive (European Union 2007/2—Infrastructure for Spatial Information in Europe) and the Preservation Plan of European Water Resources (European Commission, 2014).

To achieve the objectives of sustainable development of water resources it is necessary to consider the aspects of design and management of physical infrastructures, the quality of the environment, the economic, financial and social aspects, human health, and the health of the ecosystem. Including the criterion of sustainability among the common economic, environmental, social criteria used up to now to evaluate possible water management strategies is not easy or immediate to implement but is a fundamental element of change in the management of water resources that must involve all water systems including drinking water systems.

As regards drinking water systems, the current research topics concern the most traditional aspects of design, management and optimization (Carini, Maiolo, Pantusa, Chiaravalloti, & Capano, 2017; Cunha & Sousa, 1999; Mutikanga, 2011; Maiolo & Pantusa, 2016; Vasan & Simonovic, 2010) both the aspects related to climate change, to the growing conflict between uses, to the possibility of using unconventional water resources not only in countries historically subject to drought but also in other territorial realities (Becker, Lavee, & Katz, 2010; Depla, Jung, Baures, Clement, & Thomas, 2009; Friedler, 2001; Maiolo, Mendicino, Senatore, & Pantusa, 2017; Maiolo & Pantusa, 2017a, 2017b). The increased sensitivity to the issue of sustainability and the Community and national legislative guidelines require that currently all these research aspects are more correctly addressed and interpreted on the basis of sustainability principles and assessments. Being able to make these assessments can be very complex, also due to the sensitivity of drinking water systems which transport a product for human consumption. In order to achieve sustainable management of these systems, it is necessary to address the problem of the inefficiency of infrastructures that are not appropriate to the current sustainability criteria, starting with the materials used.

The choice of pipes material in a water distribution network is oriented by the design conditions based on hydraulic, geological, static and economic evaluations and have to be based on the cost/effectiveness ratio. The recent regulatory guidelines have made the use of cost comparison criteria more stringent in relation to the life cycle of materials and their environmental impacts. This type of assessment requires a methodology that compares the different types of materials based on their life cycle environmental impacts, such as the life cycle assessment (LCA).

The LCA method was introduced, in its current formulation, by ISO 14040/2006 standards and represents a useful tool for assessing the environmental impact associated with mass and energy flows in and out of the analyzed product. The life cycle analysis validity and importance is consolidated, because it has been known that reducing pre and post production environmental costs facilitates the environmental impacts reduction (Stavropoulos, Giannoulis, Papacharalampopoulos, Foteinopoulos, & Chryssolouris, 2016).

Regarding water systems, in the scientific literature the LCA was used to estimate the environmental impacts with different analysis details, as detailed in Table 1. Lundie, Peters, and Beavis (2004) presented an LCA application to the strategic planning process for the overall activity of Sydney Water (the largest water service provider in Australia). Stokes and Horvath (2009) presented an updated version of the decision support tool Water-Energy Sustainability Tool (WEST) for U.S. water services including a customizable LCA for each U.S. state, specific and commercial databases. Godskesen et al. (2011) applied the LCA to assess the impacts of the operational phase on three different water systems in Denmark. The objective of this study is to demonstrate that the LCA is a valuable tool for decision support, which also includes the environmental aspect. In Del Borghi, Strazza, Gallo, Messineo, and Naso (2013) the LCA analysis was applied on the

Table 1. The main literature references about LCA studies applicated to WDS

References	Aims	Objectives	Research method
Lundie et al. (2004)	Life cycle assessment for a large water and wastewater system	Comparison on the sustainability estimates (referring to the environmental, economic and social contexts) in different scenarios	LCA with a Cradle to grave approach
Stokes and Horvath (2009)	Life cycle assessment for a water supply system in reference to Energy and Air Emission Effects	Identify a replicable analysis methodologies for US water services	LCA with a Cradle to grave approach
Godskesen et al. (2011)	Comparison between the impacts associated to the processes involved in a three water system types	Verify if the LCA method, referring to some impact categories (such as greenhouse effect, toxicity, nutrient enrichment and acidification) is a valid tool to planning operation in water system	LCA with a Cradle to grave approach
Del Borghi et al. (2013)	Impact analysis of a potable water supply systems, excluding the use stage	Analysis type based on the environmental label request (as Environmental Product Declaration—EPD).	LCA with a Cradle to grave approach
D'Ercole et al. (2014)	Identify the system performance and the possible strategies to increase the sustainability level in a water system	Quantify the resources flows (input and output), linked to the necessary metabolic turnover, to guarantee the optimal operating conditions of the water system	Urban metabolic model based on LCA application with cradle to grave type
Hasegawa et al. (2016)	Optimize the replacement strategies of water systems to reduce the life cycle cost and greenhouse gas emissions	Impact evaluations in the context of continuous long-term depopulation	A synthesis of LCA and Life Cycle Cost (LCC) methodologies
Dennison et al. (1999)	LCA analysis of a potable water pipes	Identify the phases where environmental impacts may be reduced	LCA with a Cradle to grave approach
Du et al. (2012)	Evaluate the economic-environment performances for six commonly pipes material used for water and wastewater	Impact analysis, in terms of global warming potential (GWP), referring to the pipe production, transport, installation, and use phases. The consequent objective is to examine the effective validity of currently used pipe size selection criteria in a GWP analysis	Using the LCA impact estimate as based to create a monetized values through an emission penalty parameter
Barjoveanu et al. (2014)	Demonstrate the LCA study validity to describe, compare and predict the environmental performance of water systems	Quantification of environmental impacts before and after the tap system, referring to a Romanian water system	LCA with a Cradle to grave approach

methodological model Environmental Product Declarations (EPD) to a drinking water system in Sicily (Italy). An important reference is the metabolic model adaptation to the performance analysis of a water system (D'Ercole, Ugarelli, & Di Federico, 2014). This model through LCA application allows to assessment the impacts associated with the intake structures, potabilization, distribution, waste collection and depuration.

Regarding the water distribution system (WDS), Hasegawa, Arai, Koizumi, and Inakazu (2016) proposed an LCA applied to a WDS with a continuous depopulation scenario. In this study, the pipes downsizing usefulness to satisfy the variations of the population was also examined. Dennison, Azapagic, Clift, and Colbourne (1999) proposed an LCA application to compare two different pipe materials types (ductile iron and medium density polyethylene), highlighting the life cycle phases which have major impacts and proposing solutions to reduce them. Du, Woods, Kang, Lansey, and Arnold (2012) applied LCA to six water and wastewater pipe materials (polyvinylchloride—PVC, ductile iron, iron cast, high density polyethylene-HDPE, concrete, reinforced concrete) and these study results are monetized referring to the CO_2 emissions. There are other studies that consider the pipes as simple elements of a more complex infrastructure, in the overall analysis of water systems as that proposed by Barjoveanu, Comandaru, Rodriguez-Garcia, Hospido, and Teodosiu (2014), which referring to the operational phase, excludes many life cycle stages of piping materials, focusing attention on maintenance, replacement and relative wastes generated.

In Italy, the recent legislative guidelines (Legislative Decree n.50/2016), following the European directives 1386/2013/UE—2013/179/UE—2014/23/UE, introduce, as an evaluation parameter between design alternatives, the cost-effectiveness comparison through the life cycle cost. This kind of assessment should be able to synthesize environmental and design aspects and for this reason requires the use of compound indices.

In literature, therefore, several LCA applications were conducted on drinking water systems and pipelines; the aim of the work presented in this paper is to define a synthetic index useful to support the choices of the drinking water pipelines materials that takes into account both technical and environmental aspects. In particular, a LCA application was carried out to the main materials used for drinking water pipeline (10 types of materials) to evaluate the impacts associated with their production phase. For the same types of materials, the coefficient of elasticity *in situ* (ISEC), which depends on the pipes and soil characteristics, was calculated. The proposed index, *In Situ Sustainability Index (ISSI)*, is obtained as the product of the two results for ISEC and LCA.

2. Materials and methods

The pipeline choice criteria are technically depended on the hydraulic behavior (interaction between pipe and water, in relation to the hydraulic operation of the network) and the static behavior of the pipes (interaction between pipe and laying soil, in relation to the forces acting on the pipe-soil system). The static behavior of a drinking water pipeline is characterized primarily by the relationship with the soil (underground or airborne pipe), depending on the loads in relation to the system of constraints with respect to the ground: flat state or beam state.

The pipe static behavior characteristics in relation to the soil are defined depending on its rigidity, that is its aptitude not to deform due to load. Stiffness is defined by the rigidity modulus depending on the material characteristics, through its elastic modulus E, and the size of the pipe, through inertia moments I and J (the first dependent on the tube thickness alone, the second from the ratio between the thickness and diameter of the pipe).

For the laying soil, the characteristics are determined according to the its rigidity. The models that analyze the pipe-soil interaction, also define a classification ordinarily articulated into three categories: rigid, semi-rigid and flexible pipe (Davies, Clarke, Whiter, & Cunningham, 2001). Rigid pipe shows a maximum strength under load limited by an ultimate limit state without significant deformation; the semi-rigid pipe shows a maximum strength under load limited by ultimate limit state or deformation; the flexible pipe shows a maximum strength under load limited by ultimate limit state of deformation. In the rigid material category there are cement and fiber cement pipeline, among the semi-rigid pipes category have to mention steel and iron cast pipes, whereas plastic pipes are associated with the category of flexible pipeline. Each type of pipe may have one or more performance limits which must be considered by the design engineer.

In the early 1900s, Anson Marston developed a method of calculating the earth load to which a buried conduit is subjected in service. This method, the Marston load theory, serves to predict the supporting strength of pipe under various installation conditions. As reported in Tian, Liu, Jiang, & Yu (2015) on the basis on Marston work later researchers made continuous improvements and developed formulae for the vertical earth load on rigid pipes and culverts. M.G. Spangler, working with Marston, developed a theory for flexible pipe design and published his Iowa Formula for predicting the ring deflection in 1941. The Iowa Formula was modified by Watkins in 1958.

The choice of piping material is also related to the features of the laying soil that integrate static evaluation, according to Saedeleer's theory, which schematizes the static behavior of buried pipes. In the Saedeleer's theory, the uniform horizontal q reaction of the soil, due to the actions transmitted by the pipe, is proportional to the deformation Δx of the soil it self

$$q = K\Delta x \tag{1}$$

where K represents a soil rigidity coefficient, defined by the horizontal pressure that is required to apply to the soil backfill to produce a unitary deformation. This coefficient, which can range from 5 to 120 N/cm^3, depends on the depth and on the characteristics of the soil (Abu-Farsakh & Nazzal, 2005).

Therefore, the soil–structure interaction influences pipe performance and is a stiffness properties referring to the soil and pipe. The ratio of pipe stiffness to soil stiffness determines to a large degree the load imposed on the conduit (Moser, 2001). In the Watkins formula, for example, this link is expressed through the expression

$$R_s = \frac{E'D^3}{EI}, \tag{2}$$

where R_s is the stiffness ratio is the ratio of soil stiffness E' to pipe-ring stiffness EI/D^3. This quantity includes all the properties of materials, soil as well as pipe. Since for a solid wall pipe of constant cross section $I = t^3/12$ (Moser, 2001). It is worth noting that $1/R_s > 1/12$ for rigid pipes and $1/R_s < 1/12$ for flexible pipes. After these premises it is possible to define the In Situ Elasticity Coefficient (ISEC) as $1/R_s$ and, using the ratio between inertia moments I and J in function to the thickness and average pipe radius (R)

$$ISEC = \frac{EJ}{E'R^4}. \tag{3}$$

Pipes with high values of the $EJ/E'R^4$ ratio transmit to the soil the sideways horizontal pressures, negligible compared to vertical ones: this aspect defines the behavior of rigid pipes. Contrariwise, flexible pipes are characterized by a low value of the $EJ/E'R^4$ ratio.

Regarding the LCA application, its objective is to evaluate the impacts associated to the production phase of different types of pipes. A total of 10 test pipes of a different material are analyzed, chosen from the most popular ones on the European market (Steel, Iron cast, Gres, Reinforced cement concrete, Unreinforced concrete, Fiber cement, PVC, PP, PRFV, PE). The functional unit is 100 linear meter of the pipe of the material selected with the same diameter (ND 300 mm). In this work, the functional unit is independent of the number of inhabitants, water demand, velocity and slope because the LCA application is only intended to compare the environmental performance of test materials. System boundaries are from Cradle to Gate: the study excludes the transport phase, use and end of life. The analysis is limited to the assessment of the impact only of industrial processes, but the packaging operations are neglected.

Input data do not refer to specific pipelines, but represent average European values of some manufacturers (for this aim in the follow analysis the ecoinvent database was preferred to Agri-footprint, Swiss Input Output Database). In Table 2, life cycle inventory (LCI) is synthesized.

For the Life Cycle Impact Assessment (LCIA), it is possible to use many methods, which differ in purpose and structure of analysis. For example, each method uses different weight coefficients for impact assessment and for this reason the outputs comparability is not always easy (Stavropoulos et al., 2016). Among the most used methodologies there are Eco-indicator 99, EPS 2000, IMPACT 2002 +, which are specified below in reference to Jolliet et al. (2003) and Humbert, Margni, and Jolliet (2005). The methods general structure includes the classification, characterization, normalization and weighting phases. The first and the second are set, therefore present on all methods, unlike the latter. Eco-indicator 99 is a damage-oriented method. This expresses the impacts in three damage categories, which contain the impact categories. Normalization and weighting are performed at the damage category (endpoint level) caused by a European citizen in 1 year. The EPS 2000 method evaluates the external costs of a product in monetary terms ("ELU" Environmental Load Unit). In this method, to each impact category is associated a weight which, multiplied by the characterization values, allows to have all the impacts expressed in ELU. Subsequently the ELU values are multiplied by the respective evaluation factors and finally added together to obtain a single indicator. The IMPACT 2002+ method is formulated by the methodologies combination based on both the midpoint approach, which refers to the impact categories, both on the endpoint, based on the damage categories. In the Impact 2002+ method, the assessments are made primarily at the midpoint level and at the normalized damage

Table 2. Data organization for the LCA application: LCI summary

Material	Weight Pipeline (Kg/m)	Thickness Pipeline (mm)	Raw Materials	Processes
Reinforced cement concrete	310	70	Portland cement, concrete, reinforcing steel	Radial compression, painting
Unreinforced concrete	100	76	Portland cement, concrete	Radial compression, painting
Gres	100	76	Clay, chamotte, water	Extrusion, drying, painting
Fiber cement	5	40	Portland cement, polimeric fiber, cellulose fiber	Hatschek forming, painting
Steel	39	5	Steel, bitumen, PE, PP, PU, zinc coat, cement mortar	Fusion welding, painting
Iron cast	68	6	Iron cast, cement mortar, zinc coat	Fusion welding, spinning, painting
PE	11.5	12	PE, additives	Extrusion, polymerization, painting
PP	26	28	PP, additives	Co-extrusion, painting
PRFV	12	7	Glass fiber reinforced plastic, inert filler, liner	Centrifugation, polymerization, painting
PVC	10	6	PVC, additives	Extrusion, painting

level. In the first case, the evaluations are obtained by means of the midpoint characterization factor and are expressed in equivalent kilograms of the reference substance. In the second case, these assessments are calculated by means of the normalized damage factor and expressed in "points", which correspond to "pers · yr" with reference to Europe. In the IMPACT 2002+ methodology, new methods and concepts have been developed for the comparative assessment of the Human Toxicity and Ecotoxicity categories, while for the other categories the methods have been transferred or adapted by other methods, such as Eco-indicator 99. Impact 2002+ was used for impact assessment because provides a new concept for the comparative assessment of toxicity and ecotoxicity humans, which in a contest of drinking water management, have a considerable weight. The Impact 2002+ method specifies the impact in damage categories (human health, ecosystem quality, climate change, resources) and impact categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy and mineral extraction). In LCA method application, the normalization phase is important because it clarifies the next stage of interpretation. Relate to Impact 2002+ method, the normalization factor is determined by the impact ratio per unit of emission divided by the total impact of all substances in the specific category (per person per year): the normalization factor identifies the total impact of the category divided by the total European population (Humbert et al., 2005). The normalization factors for the Impact 2002+ damage category are shown in Table 3. For the LCA application SimaPro 8.4.0. (PRé Consultants distributed) software was used.

After calculating the ISEC value and the impacts associated with the life cycle of the pipe materials (LCA value), it is possible to proceed to the ISSI calculation, defined as:

$$ISSI = ISEC \cdot LCA. \qquad (4)$$

The simple analytical structure makes this index easy to use and useful for interpretations and comparisons. This methodology is useful for comparing alternatives, as well as those based on the scores and weights analysis, whose value is known (Chowdhury & Squire, 2006; Decancq & Lugo, 2013; Maiolo & Pantusa, 2018). For this reason, the ISSI index is suitable of this study.

3. Results and discussion

The analysis of the behavior of the ISEC is described in Table 4 with an example reference to the nominal diameter ND 300 for the main types of piping material at equal conditions and laying soil (E' = cost).

The ISEC values are shown in Figure 1.

The trend of the ISEC, at the same conditions of laying and diameter of the pipes, obviously shows a dependence on the type of pipe material characterized by the Elastic Modulus (E) which

Table 3. Normalization factors for the damage categories of impact 2002+ method related to Western Europe (Humbert et al., 2005)

Damage categories	Normalization factor referring to Q2.2 version	Unit
Human Health	0.0071	Disability-Adjusted Life Year DALY/point
Ecosystem Quality	13,700	Potentially Disappeared Fraction of species over a certain amount of m2 during a certain amount of year PDF.m2.y/point
Climate Change	9,950	kg CO_2 into air/point
Resources	152,000	MJ/point

Table 4. Pipe classification with characteristic values. ISEC for different types of materials referring to ND 300 mm

Material	Outside diameter (mm)	Thickness (mm)	E (N/mm^2)	J (cm^4)	ISEC
Reinforced cement concrete	465	70.0	10,000	36,544	0.72
Unreinforced concrete	432	65.0	10,000	35,661	0.70
Gres	370	76.0	40,000	37,406	2.95
Fiber cement	334	40.0	18,000	28,262	1.01
Steel	324	5.0	206,000	29,845	12.14
Iron cast	326	5.7	105,000	5,708	1.18
PE	315	21.1	880	11,359	0.02
PP	328	28.6	1,200	22,701	0.05
PRFV	330	7.0	15,000	6,918	0.20
PVC	355	6.2	2,940	6, 177	0.03

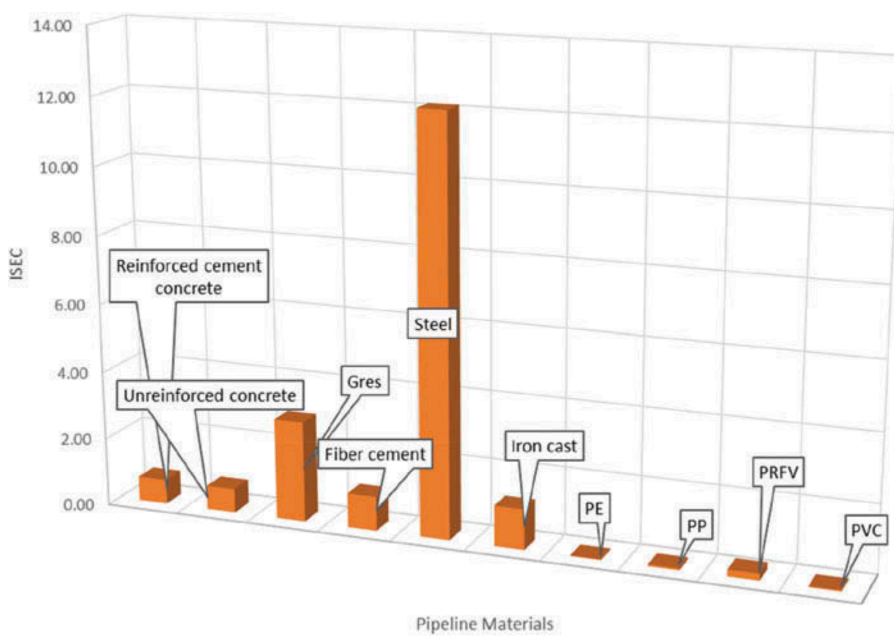


Figure 1. ISEC index values referring to the test materials.

evaluates the tendency of the material to deformation. The trend of the Elastic Modulus is characterized by lower values of flexible materials compared to materials with increasing rigidity. For this reason, metallic materials have the highest values of module *E*. Furthermore, the *E* values thicken in the range 50,000 N/mm^2, exclusion of metal materials.

Regarding the LCA application, the total impact associated to the 10 types of pipes is summarized in Table 5. As is well known, the output of the LCIA is a value that summarizes the environmental profile of the unitary functionality analyzed. The comparison of the normalized impacts associated with the 10 test materials, referred to each damage category, is show in Table 5, while the total impacts are summarized in Figure 2.

By classifying the impact on categories of damage (Figure 2), it is evident that the greatest contribution is related to human health.

Table 5. Overall impact evaluation for test pipeline. LCIA summary

Material	Human health	Ecosystem quality	Climate change	Resources	Impact Assessment
Reinforced cement concrete	0.00085	0.00009	0.00096	0.00060	0.00251
Unreinforced concrete	0.00035	0.00004	0.00043	0.00038	0.00120
Gres	0.00037	0.00004	0.00040	0.00041	0.00122
Fiber cement	0.00040	0.00005	0.00049	0.00050	0.00144
Steel	0.00232	0.00039	0.00109	0.00106	0.00486
Iron cast	0.00010	0.00001	0.00016	0.00018	0.00046
PE	0.00069	0.00007	0.00081	0.00117	0.00274
PP	0.00097	0.00008	0.00107	0.00148	0.00360
PRFV	0.00358	0.00012	0.00110	0.00104	0.00583
PVC	0.00326	0.00006	0.00088	0.00110	0.00531

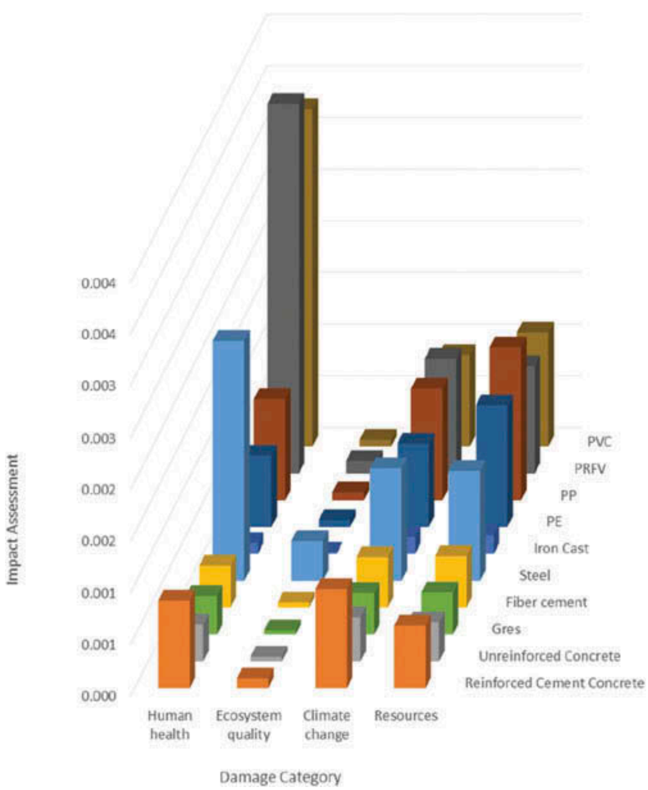


Figure 2. Comparison of the normalized impacts associated with the 10 test materials, using impact 2002+ damage category.

The importance of the impacts of Human Health category (expressed as Disability-Adjusted Life Years) is due to the highest impacts, evaluating as midpoint level, of Respiratory inorganics category associated to PRFV. Today, this impact category is very important because it measures the impact in kg PM2.5 into aireq. The Particulate Matter (PM2.5), most commonly referred to as aerosol, is one of the likely causes of cancer (Eftim, Samet, Janes, McDermott, & Dominici, 2008). The high values of Human toxicity (kg Chloroethylene into aireq) refer to PVC pipes. Chloroethylene (VCM), in fact, is very used for PVC production and causes serious human health damage (ATSDR, 2006). Polymeric piping (such as PVC, PRFV) can release organic and phosphorus compounds which facilitate microbiological regeneration and biofilm formation (Yu, Kim, & Lee, 2010).

Figure 2 shows a low overall contribution of the damage category Ecosystem quality and the comparable total related to Climate change and Resources. However, it is useful to detail the materials contribution associated to the four damage categories. Related to Human health, the impact associated with the test materials has similar values, except for Steel, PVC and PRFV which have the greater impacts. Concerning Ecosystem quality category, the impact associated to the test materials assumes similar values except for Steel. With regard to Climate change, the impact values associated with the test materials can be classified into two areas. In the first area (the lower impact) there are Fiber cement, Gres, Unreinforced concrete and Iron cast, while in the second (the greater impact) there are Steel, Reinforced cement concrete, PE, PP, PRFV and PVC. Regarding Resources, the impact associated with the test materials has a comparable value except for Steel, PVC, PRFV, PE and PP, which have the greater impacts.

Therefore, Figure 2 summarizes one of the main purposes of this research, the sensitivity evaluation of the pipe material choice in water systems. It is also evident that the plastic materials, which are widely used, have higher impact percentages than others materials. This detail is more evident in Figure 3, which classifies materials based on the impacts associated with the life cycle, referring to the results of the LCA application. Figure 3, compared with Figure 2, proposes an assessment of the overall impact of damage category contributions in order to associate a single impact value to the life cycle of each test material so that it can quantify sustainability. In Figure 3, the higher values of the ordinates correspond to a greater impact and a consequent less sustainable life cycle. It is therefore associated a high environmental cost to polymeric materials (PRFV and PVC), whereas traditional materials have smaller impacts. In particular, steel pipes show an isolated value confirming the high environmental impacts associated to the steel industry.

Once the ISEC and LCA values have been determined, the ISSI index values has been calculated on the basis of Equation (4). The results are shown in Table 6 and in Figure 4.

The graph in Figure 1 shows that less elastic materials (ISECmin) are PE, PP, PVC, while the more elastic ones (ISECmax) are Steel, Iron cast and Gres. This hierarchy is modified by considering the

Figure 3. Impact assessment of test materials using the LCA method.

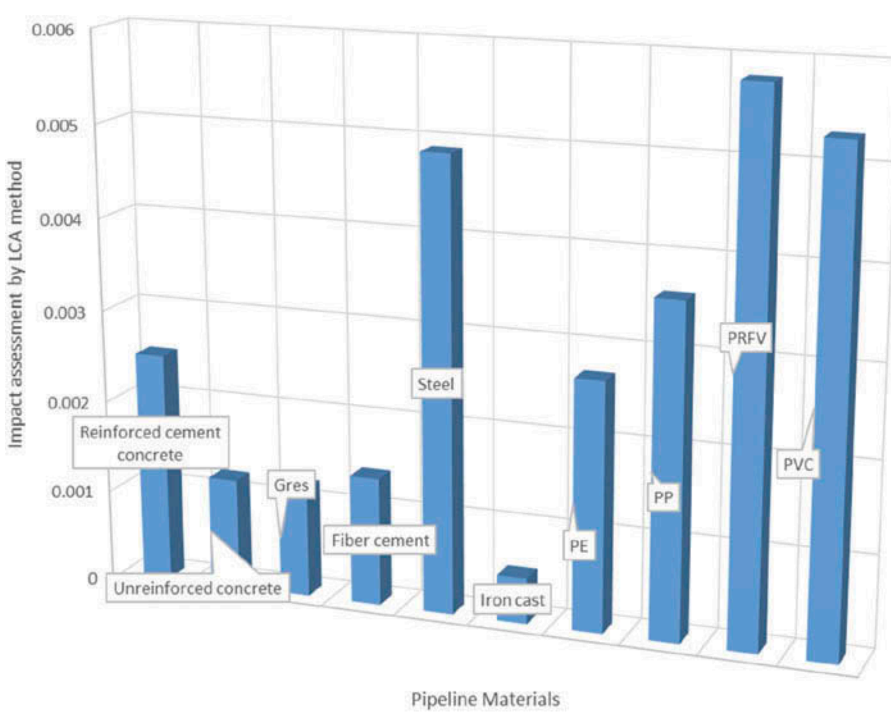
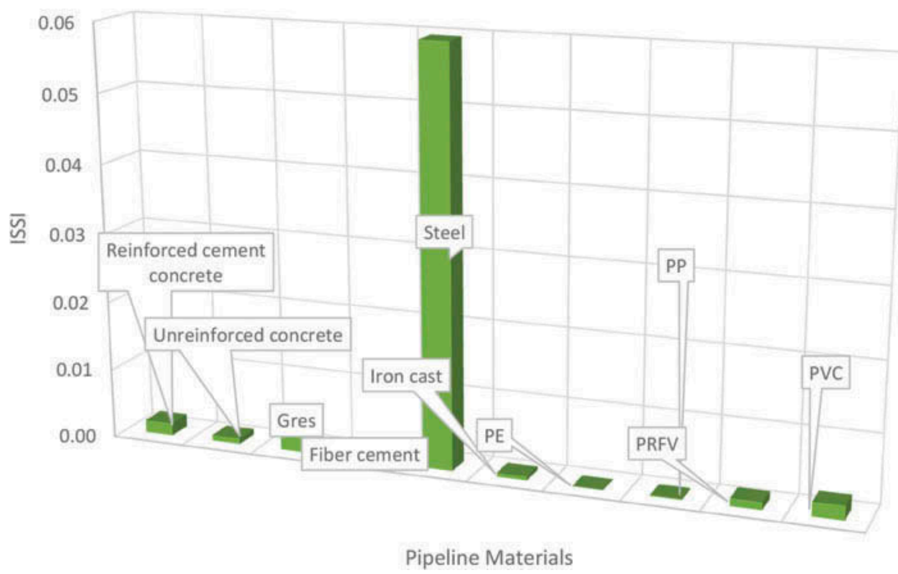


Table 6. ISSI value for the test materials

Material	ISEC	LCA	ISSI
Reinforced cement concrete	0.72	0.00251	0.0018
Unreinforced concrete	0.70	0.00120	0.0008
Gres	2.95	0.00122	0.0036
Fiber cement	1.01	0.00144	0.0014
Steel	12.14	0.00486	0.0595
Iron cast	1.18	0.00046	0.0006
PE	0.02	0.00274	0.0001
PP	0.05	0.00360	0.0002
PRFV	0.20	0.00583	0.0012
PVC	0.03	0.00531	0.0021

Figure 4. ISSI associated to the test material.



graph in Figure 3, which shows that the highest impact is associated to PRFV, Steel, PVC, whereas the most sustainable materials are Unreinforced concrete, Iron cast and Gres. It is possible to redefine a synthetic hierarchical order by defining the ISSI index (Figure 4) which, by linking traditional assessments (ISEC, Figure 1) to environmental assessments (LCA, Figure 3) provides a single parameter that allows to orient the design choices in the definition of drinking water piping materials. It can be seen that the Reinforced cement concrete keeps its position unchanged, but other materials such as the PRFV (which has the highest impact value) and Gres (which has not a high impact value) show a substantial changes.

The ISSI index creates a link between parameters not only related to static or intrinsic aspects of the material type, but with equals need for use for rigid, semi-rigid or flexible materials, allows to identify the most sustainable choice. With the same static-hydraulic performance, the results show that the material with a higher ISSI value is less sustainable than another material with lower ISSI.

As shown in Table 1, the scientific literature on WDS and LCA proposes several studies, which, however include the pipeline analysis in a much broader contex with objectives mainly linked to the planning phase (Godskesen et al., 2011; Hasegawa et al., 2016; Lundie et al., 2004). The shown ISSI, on the other hand, is more useful in the design phase, as an additional criterion to the traditional ones for the pipeline choise. Dennison et al. (1999) and Du et al. (2012) described an approach similar to one proposed in this work, but more general (from Cradle to Grave). Instead this work presents a focus on the initial part of the pipes life cycle (from Cradle to Gate) to highlight the desire to intervene on the starting stages to not load those phases beyond the Gate. In this respect, this work wants to plan and incentivize a sustainable production mechanism, able to reduce the emergencies related to the disposal phase.

For this reason, the proposed ISSI index represents an attempt at innovation to create a link between technical and environmental assessments as a basis for sustainable design.

4. Conclusions

The evolution of the materials and the innovations introduced has brought about significant improvements in the hydraulic and static behavior evaluation of the pipes. Increasing environmental sensitivity has mainly affected on the cost-assessment criteria, also in terms of environmental sustainability. The introduction of the LCA method, as a complementary tool for orienting this choice, is a useful technical and technological support as it allows to measure the level of sustainability of piping materials. The shown analysis proposes a benchmarking between different pipeline materials for the drinking water system, through an index of sustainability (ISSI) that, by integrating the ISEC coefficient with the LCA results, provides an additional criterion which completes the assessments for the design choices of drinking water systems. Sustainability analysis of the 10 selected test materials has shown that polymeric materials (such as PVC, PRFV) are associated with higher impacts linked to the emissions into the environment of harmful human health. The proposed index ISSI can be considered integrative to the traditional criteria for water systems pipeline choice, because it summarizes the environmental assessments (LCA) and technical assessments (ISEC). The ISSI index formulation represents an attempt to summarize two essential aspects of design practice and can represent a support to the selection criteria for water piping materials which can't replace traditional static techniques, but it is proposed to support and integrate them. The usefulness of the proposed methodology lies also in the simplicity of the analytical formulation, which makes it expeditious and easy to interpret.

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