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Multi criteria decision analysis to set the priority of interventions in water distribution systems

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Abstract

Water distribution systems play a fundamental role due to their impact on public health, food, agriculture and energy and consequently, they are identified as critical infrastructures. Integrated urban water management is affected by critical issues that may interfere with the achievement of the best management practice. The work shows a methodology for the identification of interventions priorities in a region where several water distribution systems, with different criticalities, coexist. As metric for critical issues, IWA PIs has been chosen. Multi-criteria Decision Analysis (MCDA) is applied to obtain a sorting of critical issues and thus to define the priorities in the investment planning. The aim is to provide a tool that supports the consistency check between criticalities and interventions planning. The methodology has been applied to 15 management areas within an homogeneous region in the North of Italy.

1 Introduction

In order to guarantee a sustainable future one of the most ambitious challenge is represented by a prudent and efficient water resources management (Ceola, Montanari, Krueger, & al., 2016). Water distribution systems play, indeed, a fundamental role due to their impact on healthcare and public health, food, agriculture and energy and consequently, they are identified as critical infrastructure. Both qualitative and quantitative data concerning physical infrastructure, as well as customers, governance and services, at the appropriate scales, can support various metrics to measure the criticalities. Subsequently these metrics are able to identify the most effective interventions to increase the resilience of water distribution systems (Haider, Sadiq, & Tesfamariam, 2014). Resilience is a concept that is increasingly used to refer to the capacity of infrastructure systems, composed of interacting parts that operate together to achieve a target, to be prepared for, and able to

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respond to, long-term changes of the socio-economic and environmental contexts (Wong-Parodi, Fischhoff, & Strauss, 2015) . A frequently used approach in water resources management consists in Multi criteria Decision Analysis (MCDA), which allows to prioritize alternatives, to consider multiple aspects, often conflicting and subject to constraints, based on technical, environmental and socioeconomic criteria (Cinelli, Coles, & Kirwan, 2014).

Actually, the correspondence between critical issues of WDSs and performance indicators, even when the criticality is limited to a particular aspect, is not an univocal relationship. Also, the choice of performance indicators used in literature (Haider, Sadiq, & Tesfamariam, 2014) or the definition of new indicators is a key step that influences the MCDA analysis and thus the final priority of interventions. It has not been possible to assign a unique correspondence to some criticalities since they can be observed from a variety of points of view, thus the need for the definition of a set of PIs arises. Since the set of PIs has to be able to give a unique final classification of priorities, an aggregation process is applied. The methodology supports the identification of interventions priorities when more water distribution systems, with different criticalities, are present. Multi-criteria Decision Analysis is applied to classify critical issues and thus define the priorities in the investment planning. The aim of the methodology is to provide a tool to support the consistency check between criticalities and interventions planning.

2 Methodology

The methodology to identify the priority of interventions in water distribution systems is shown in Figure 1. Herein Multi Attribute Utility Theory (MAUT) (Cinelli, Coles, & Kirwan, 2014) has been used as MCDA, but others approaches could be used to classify critical issues and therefore, to order the interventions.

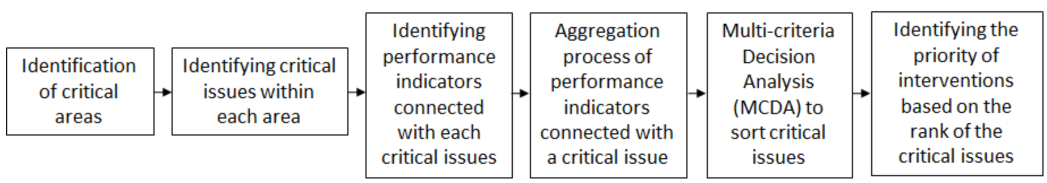

Figure 1: Methodology to identify the priority of interventions in water distribution systems

The first step requires the definition of areas in water distribution system in which potential criticality could occur, as indicated in Table 1. Subsequently, the attention is focused on bring out the critical issues within each area. The necessity to estimate the magnitude of each critical issues finds support in using performance indicators. Actually, the correspondence between critical issue and performance indicator, even when the criticality is limited to a particular aspect, is not an univocal relationship. Indeed, the critical issue can be observed from a variety of points of view, a set of PIs can be associated to it. Afterwards, since the set of PIs has to be able to give a unique final judgement, an aggregation process is often applied.

2.1 Aggregation process

In the aggregation of PIs, some aspects have to be considered. The value of performance indicators may increase or decrease with improving performances, thus the best behaviour could correspond to the highest or the lowest indicator’s value. Also, such performance indicators may be stated by means of different measurement units, thus a normalisation process is required in order to make PIs comparable (Haider, Sadiq, & Tesfamariam, 2016). Finally, benchmarks are needed, namely reference values that allow one to compare the considered case study with other contexts.

Criticality in knowledge of infrastructures
Criticality in water supply
Criticality in water treatment plants
Criticality in water distribution
Criticality in consumers service
Criticality in general management
Criticality in knowledge of infrastructures

Table 1: Areas with prospective criticality in water distribution systems

The normalisation phase represents the first step of the aggregation process of the performance indicators to obtain a homogeneous metrics to measure the criticalities. According withv (Stahre, Adamsson, & Mellstrom, 2008) [5], considering a region with a set of M management zones and a set of N performance indicators associated to a criticality, the normalized value scorePIij of each indicators PIj for the management zone i, is obtained with the eq. (1):

$$scorePI_{ij} = \frac{actual\ value\ PI_{ij} - worst\ value\ PI_j}{best\ value\ PI_j - worst\ value\ PI_j} \cdot 90 + 10 \quad i = 1, \ldots, M; j = 1, \ldots, N \tag{1}$$

where *actual value* PI_{ij} is the current value that the indicator PI_j assumes in the management zone i, while *best value* PI_j and *worst value* PI_j are the reference values assumed by the indicator PI_j for best and worst context, respectively. In this work a polylines with two segment was used, imposing the vertex in the median value.

The second step consists in the selection of the importance's order of performance indicators PI_j within the set N. In a shared procedure, the decision makers take part in setting the priority among the performance indicators. Subsequently, PI_j are put in order of ascending importance, allowing that some of them may share an ex-aequo position. From the ranking of the PIs, it is possible to obtain the weight assigned to each PI_j given by the ratio of his position and the sum of all the positions as defined in eq. (2):

$$weight_{PI_j} = \frac{position_{PI_j}}{\sum_{j=1}^{N} position_{PI_j}} \tag{2}$$

Thus, the normalised weighted value v_{ij} of PI_j is given by eq. (3):

$$v_{ij} = weight_{PI_j} \cdot scorePI_{ij} \tag{3}$$

The third step is the aggregation process itself. For the aggregation phase the method proposed by Haider et al. (Haider, Sadiq, & Tesfamariam, 2016) has been applied. It is based on the geometrical distance of v_{ij} with respect to the *positive ideal solution* (PIS) and to the *negative ideal solution* (NIS) that correspond to the product of the indicator's weight and the extreme upper and lower values respectively.

Assuming that PIs have been normalised in a scale ranging from 10 to 100 (see eq. 1), for the *j*-th indicator, NIS is thus vj− = wj·10 and PIS is vj+ = wj·100. Once that PIS and NIS are obtained for each PI_j within the set N, the Euclidean distances of the N weighted normalised values with respect to the PIS and the NIS are computed:

$$Y_i^- = \sqrt{\sum_{j=1}^{N}(v_{ij} - v_{j-})^2} \tag{5}$$

$$Y_i^+ = \sqrt{\sum_{j=1}^{N}(v_{ij} - v_{j+})^2} \tag{4}$$

v_j+ and v_j- represent respectively the PIS and NIS for the *j*-th indicator that has to be aggregated. Thus, the aggregated indicator, for the management zone *i*, is given by the final normalised value P_i, as in eq. (6):

$$P_i = \frac{Y^+}{Y^- + Y^+} \cdot 100 \qquad i = 1, \ldots, M \tag{6}$$

Indeed, since one of the aims is measuring the criticalities through PIs, this expression implicates that an higher value of P_i corresponds to a higher level of criticality (and not to a higher level of performance as in (Haider, Sadiq, & Tesfamariam, 2016).

3 Case study

3.1 Critical issues

The Italian Regulatory Authority for Energy, Networks and Environment (ARERA) is an independent body created under Italian Law No. 481 of 14 November 1995 for the purposes of protecting consumer interests and promoting the competition, efficiency and distribution of services with adequate levels of quality, through regulatory and control activities. According to the Regulation (ARERA, 2016), critical issues, grouped in critical areas, were defined for the integrated urban water management, with the aim of associating them to the interventions presented in the investment planning. In this work, the critical issues shown in Table 2 were chosen to illustrate the methodology: insufficient water supply system (A1.1); inadequate physical condition of distribution pipes (B1.1.); high level of pipe's break (B1.4); high level of water losses along the distribution network (B4.1). IWA performance indicators system (Alegre & al., 2006) was chosen as metrics to be associated to them, but clearly the methodology is independent by the used PI system. As shown in Table 2, critical issues A1.1 and B4.1 are suitable to be linked with more than one performance indicator, thus for these, the aggregation process was applied.

Critical issues	IWA PIs
A1.1 Insufficient water supply system	WR1 – Water resources availability WR2 – Own water resources availability
B1.1 Inadequate physical condition of distribution pipes	Op18 – Mains replacement
B1.4 High level of pipe's break	Op31 – Mains failures
B4.1 High level of water losses along the distribution network	Op23 – Water losses per connection Op24 – Water losses per mains length Op25 – Apparent losses Op26 – Apparent losses per system input volume Op27 – Real losses per connection Op28 – Real losses per mains length Op29 – Infrastructure Leakage Index (ILI)

Table 2: Critical issues considered

Firstly, PIs were calculated for 15 management areas within an homogeneous territory in the North of Italy, based on data collected in 2014. As far as water losses are concerned, Figure 2 shows the values assumed by the critical issue B4.1 in the management zones depending on all the possible combination of the weights of associated IWA PIs, as indicated in Table 2.

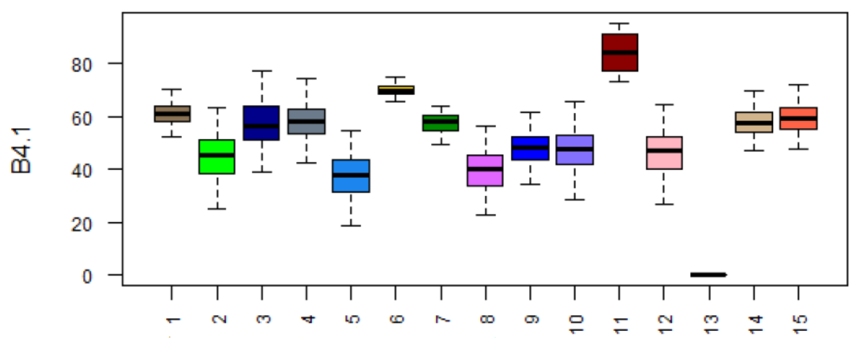

Figure 2: Values assumed by the critical issue B4.1 in the management zones depending on all the possible combination of the weights of associated IWA PIs, as indicated in Table 2

3.2 Multi-criteria Decision Analysis

Multi Attribute Utility Theory (MAUT) has been applied to the priority of the critical issues considered in Table 2, which identifies those aspects related to WDSs that require more investments. Since management zones have not the same dimensions, their importance has to be defined with regard to characterizing parameters. In this case, system input volume, number of connections and length of WDSs were chosen. Even if these parameters are not entirely independent, they can give an overall idea of the consistency of the infrastructure. Finally, MAUT analysis was carried out to evaluate the strategic importance of the management areas within the entire region. Obtained classification of critical issues is shown in Table 3, in which higher values indicate higher priority of interventions for the related critical issues in the considered region.

Criticality	Decisions vector
A1.1	0.65
B1.1	0.57
B1.4	0.02
B4.1	0.59

Table 3: Classification of critical issues by MAUT analysis considered

Conclusion

The necessity of investment for water distribution systems, and in general for the urban water management, requires a measure of the critical issues present in order to define a priority in the criticalities. This approach allows to balance a coherence between problems and amount of investment, subsequently to verify the impact of the intervention in the efficacy in reducing the criticalities. The methodology has been presented by an application related to water distribution networks, focusing the attention on the criticalities that concern insufficient water supply systems and high level of water losses. The procedure has a general effectiveness, thus can be applied to the integrated urban water management.

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