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Indicators and a Neuro-Fuzzy Based Model for the Evaluation of Water Supply Sustainability

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Abstract In the field of water management, the evaluation of sustainability has no universal methodological approach nor any consensus regarding the definitions of sustainability or sustainable development. There is an essential need therefore for a precise definition of sustainability in different water management fields. This paper deals with the sustainability of one part of urban water management, namely a water supply. A precise definition of a sustainable water supply system is given, together with a methodological framework that quantifies the degree of water supply sustainability. The proposed framework relies on the proposed quasi-strong sustainability concept, its components (dimensions), their particular relationships and corresponding indicators representing individual processes in the water supply system and utility. The processing of indicators is performed through a joint fuzzy logic/neural network (ANFIS) model. In order to evaluate each sustainability component, separate ANFIS models were created whose results were aggregated into a single result (sustainability index). According to the presented framework, sustainability is evaluated for 17 public water supply systems/utilities in Croatia.

Keywords Water supply system sustainability · Sustainability quantification · Sustainability indicators · Neuro-fuzzy evaluation of sustainability

1 Introduction

Sustainable development (SD) and sustainability are defined in a variety of ways. For different researchers they have a different meaning and different concepts and methodologies have been proposed to evaluate sustainability (Palme and Tillman 2009).

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SD and sustainability are often used synonymously but there is a subtle difference that is especially relevant in terms of their evaluation. SD should be understood as a process, while the final state of that process, in which all required criteria and conditions are fulfilled, is a state called sustainability (Simonovic 2001, Juwana et al. 2012).

In general, the sustainability assessment of water systems can be divided into three methodological procedures (Adinyira et al. 2007) that have been developed successively over time, but which are still in use today and which are mutually complemented, enhanced and interconnected. These procedures are based on numerous *economic approaches*, *life cycle assessment* and the use of *performance indicators* or *sustainability indicators* (SIs).

Additionally, some authors evaluate sustainability through specific indicators (often called *criteria* or *measures*) in the form of time series through risk assessment (Loucks 1997, Kjeldsen and Rosbjerg 2004, Sarang et al. 2007). The main idea is based on the fact that the system (or process) can perform in a satisfactory or unsatisfactory manner. Indicators (in general: *reliability*, *resilience* and *vulnerability*) are calculated based on the number of occurrences of unsatisfactory conditions (ASCE 1998).

The use of advanced computer technologies and tools, as well as multi-criteria analysis and systems theory are considered to be particularly useful in the evaluation of sustainability (Soroczynski 2002, Karleusa et al. 2010).

This paper deals with the sustainability evaluation of a water supply system (WSS), its quantification in particular. It is hypothesized that quantification relies on measurement (*a sustainability index*) representing the distance from the state of the system that is defined as sustainable, and that the index can be calculated through a joint *fuzzy logic* and *artificial neural network* model for which SIs are used as input variables.

2 Research Methodology

The research was conducted through four main steps.

The first one included theoretical research in order to perceive common elements of different definitions regarding sustainability, and to gain insight into different frameworks and SIs used for the evaluation of sustainability.

The second step pertained to the design of a complete framework for WSS sustainability evaluation. The goal of this step was to define the basic elements of the evaluation model, namely, a suitable calculation method, input variables and boundary conditions.

Third step dealt with the model creation, optimization and testing, while the fourth step included the practical use of the created model for sustainability evaluation of several WSSs.

In section 3 theoretical considerations regarding water supply sustainability are presented from which the definition of the sustainable WSS and the framework for its quantification are derived.

In section 4 the definitions and explanations of SIs are given, wherein each indicator represents a particular process in the WSS. In that way a set of the same type of indicators represent one component of sustainability (e.g. economy). For all indicators reference values, representing sustainable WSS, are given. These reference values are used to measure how far a particular process in a WSS is from its benchmark process in the sustainable WSS.

The section 5 explains the creation, the optimization and testing of the model. In particular, the use of *artificial neural network* for fuzzy rules creation is explained so that the defined fuzzy inference system reflects introduced quantificational framework from the section 3.

The sustainability of 17 public WSSs in Croatia is evaluated with the created model. The process of data collection and evaluation is described in section 6, while the results are discussed in section 7.

Section 8 provides a summary of the paper, together with the elements of its original contribution.

3 The Concept of Water Supply System Sustainability and the Quantification Framework

SD by definition includes three interrelated components (environment, society, economy), also called dimensions. Since the subject of this paper is the WSS, the analysis of its sustainability, due to its inherent characteristics, must contain additional components such as the technical and institutional component (Guio-Torres 2006, Chen et al. 2012, Carden and Armitage 2013).

The technical component recognizes all the technical characteristics of the system, its infrastructure, operating conditions, required water quality and the efficiency of the water and energy use. These characteristics thus directly affect the environmental, social and economic aspects of the system. The institutional component represents water utility management whose decisions are also affecting processes in the system. Thus, the analysis of interactions between all the components (and processes) is needed.

Interaction between the components can be considered through the weak or strong sustainability concept by which the reduction of natural resources can be (weak sustainability) or can not be (strong sustainability) compensated by human-made resources. One of these two fundamentally different concepts should be used as the basis for the quantification framework and the selection of appropriate concept should suit the system (or process) being analysed.

Different authors as well as institutions have given different definitions regarding WSS sustainability.

From these definitions, it can be concluded that a sustainable WSS has a rather dominant environmental and social component. It must meet social needs now and in the indefinite future, and at the same time must not compromise the integrity of the ecosystem or the integrity of the hydrological cycle.

One issue that arises is that society and the ecosystem find themselves competing for water resources, thus the integrity of the ecosystem becomes a concern. Since all the processes in the ecosystem are not entirely understood or known, it is not possible to grasp the overall human impact on the ecosystem and to be sure of the preservation of its integrity. Even acting within the carrying capacity cannot guarantee that an action in one place will not affect some distant part of the ecosystem.

In this sense a strong sustainability concept must be applied. It is certain that the integrity of the ecosystem will not be endangered if water for human needs is not taken at all from the natural environment. This would imply taking water from a natural environment only once and then recycling it from the built environment, primarily from a sewage system. The replenishment of additionally required quantities can be made from storm water (drainage system).

This, of course, requires significant amounts of energy, and in order to be consistent with the integrity of the ecosystem, all energy needs must be met independently of the natural environment. This means not only to use energy from renewable sources but to use energy from renewable sources owned and controlled by the utility alone. Own control of energy production is important since it increases operating independence. In this way a system is less vulnerable to external processes, such as power failures (since electricity is primarily used) coming from some distant power station that could interrupt the supply of water. Thus, the control of all the processes in a system imposes as a necessity for achieving sustainability.

For such a system its economic performance must be adequate and should not seek only to maximize profit as a primary goal. All the revenue must cover the costs of employees, system operation, maintenance costs and provide longevity by covering the amortization costs. Likewise, its technical aspect has to be extraordinary and all customers must have ultimate trust in it.

Thus, WSS sustainability is achieved through the effectiveness of each sustainability component. This effectiveness is achieved by maximizing the efficiency of positively perceived processes and minimizing negatively perceived aspects within each component. For this, all processes in the system must be quantifiable in order to evaluate their efficiency.

According to the above, a compromise between strong and weak sustainability is proposed as the basis of the quantificational model. In this way, compensation between sustainability components is possible, but with the restrictive effect for the environmental component. If some process adversely affects the environment, restrictions are imposed, resulting in a low value for sustainability index. This concept can be called quasi-strong sustainability, Fig. 1.

In the mathematical model, the possibility of resource compensation between all components is retained in order to evaluate the impact that various processes of one component have on the environmental component.

In the case of an integral urban water cycle sustainability analysis different aspects of the sewage system (its components and relevant processes), must be included in the analysis as well.

4 Sustainability Indicators

The separation of a particular process from a larger system (or a system from its environment) is possible only in the case where the interaction with other processes in the system can be ignored due to little influence and/or negligible interaction.

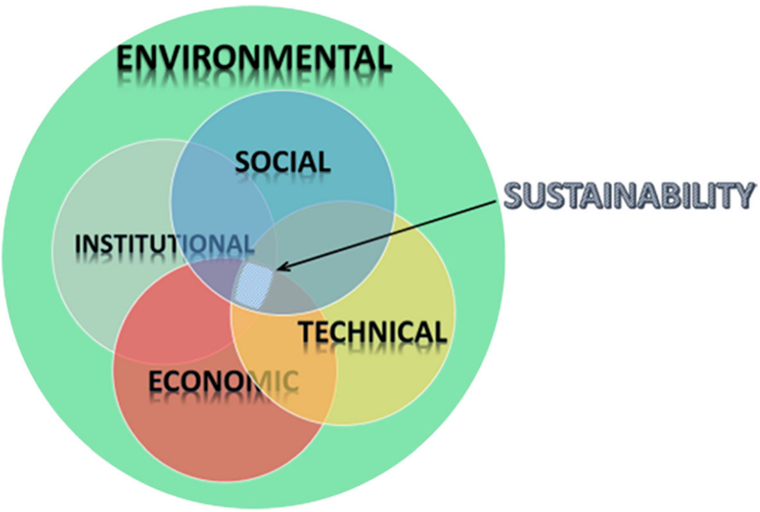

Fig. 1 A quasi-strong sustainability concept with sustainability components and their trade-offs

Therefore, an integral part of any sustainability analysis should be the system theory, with particular emphasis on system dynamics, focusing on the interaction between the components of the system. Therefore, the WSS and the water utility are viewed as a single dynamic system.

This dynamic system is characterized by internal and external processes that are represented by SIs. The internal processes take place in the components themselves and the external processes between them.

Spatially remote processes which do not affect or could not be connected with the WSS are ignored. Other processes, having some impact, are taken into account as resulting states (SIs values) occurring at the boundary of the WSS.

The processes are characterized by time changing states, thus changing indicator values that are measurable (observed) on a certain and known scale. Therefore, a SI is quantitative (measurable) information about the current state of a certain process, with clearly defined limiting values (Bell and Morse 2008, Singh et al. 2008, Leeuwen et al. 2012), and the input variable in the mathematical model.

Since the WSS is characterized by different processes, numerous different SIs are used to represent it. Nowadays, about 20 indicators are usually used in sustainability studies (Popawala and Shah 2011, Leeuwen and Marques 2012). Here, the definition of SIs was based on a *top-down* approach were all indicators are defined by the researchers themselves. Also, the possibility of practical application is included since relevant and substantial sources of information can be found among WSS performance indicators. This principle was adopted as a benchmarking system (particularly the International Water Association (IWA) benchmarking system) is increasingly used in water supply practice in recent years, especially in water loss accounting (Alegre et al. 2006).

SIs are defined in a way that more processes are included in a single indicator through its relative value, thus as the ratio of the resulting state in the total value of the process (for example, the ratio of real water losses and total abstracted water). This approach eliminates the size effect of the system (so a comparison between different WSSs is possible), the occurrence of different measurement units, as well as issues regarding SIs aggregation. In addition, an indicator limit value becomes intuitively obvious. For the positively perceived value (state) of the process, the limit value tends towards the number 1.0 or the number 0.0. These values are set as the SIs target values.

For each component, except for the economic component, indicators are grouped in two sets representing criteria (called *sustainability criteria*) that should be met in order to achieve component effectiveness. Such a classification was made in order to easily gain insight into the part of the system that shows inefficiency. Table 1 lists all the sustainability components and the criteria, together with the corresponding indicators.

SIs thus represent the resulting states of technical, economic, environmental, social and institutional processes in the system/utility in a certain time frame.

According to the above, the evaluation of water supply sustainability covers the utility service area and the water supply infrastructure within a period of one year. The time series analysis is considerably limited since utilities usually record the required data as a single, annual value. Most of the benchmarking indicators are usually recorded annually while going back only a few years.

Technical component indicators are covering various adverse situations that occur during the regular operation of the WSS, taking into account the system's energy independence and the efficiency of energy use.

Table 1 Water supply sustainability components, criteria and indicators

Sustainability components (Dimensions)	Component criteria	Sustainability indicators
A Technical	A I. Operational effectiveness	1. Water supply reliability, α_t [1]; 2. Water resources independence, k_n [1] 3. Reliability of water quality, α_h [1] 4. System vulnerability, v_t [1] 5. Relative efficiency of infrastructure, u_i [1]
	A II. Energy effectiveness	1. Energy independence, e_n [1] 2. Water distribution efficiency, e_p, [1]
B Economic	B I. Economic effectiveness	1. Current ratio, l_t [1] 2. Stability ratio, s_f [1] 3. Debt ratio, z [1] 4. Equity ratio, v_f [1] 5. Asset turnover ratio, $o_{uk,i}$ [1] 6. Overall profitability ratio, $p_{e,uk}$ [1]
C Environmental	C I. Effectiveness of water resources use	1. The use of recycled water, q_{rc} [1] 2. Water resources availability, q_{rvr} [1] 3. Water resources utilization, u_r [1]
	C II. By-products minimisation	1. Chemical sludge production, m_c [1] 2. Sewer disposal of water treatment sludge, m_k [1] 3. Utilization of by-products of water treatment, m_i [1] 4. Greenhouse gases emissions, k_{GHG} [kg CO_2e/m^3]
D Social	D I. Meeting end user needs	1. Water supply network coverage, p [1] 2. Complaints on quality of service, z_u [1] 3. Water pricing policy, c_v [1] 4. Cases of illness caused by poor water quality, b [1]
	D II. Informing end users and their involvement	1. Level of informing end users, i [1] 2. End user involvement, n_r [1].
E Institutional	E I. Management effectiveness	1. Benchmarking programme participation, bp [1] 2. Water consumption control programme, p_s [1] 3. Employee retraining, t_z [1] 4. Unbilled consumption, p_l [1] 5. Non-revenue water, q_{nv} [1]
	E II. Systems maintenance effectiveness	1. Billed water metering, m_p [1] 2. Work-related injuries, k_o [1] 3. Elimination of water system failures, k [1] 4. Water system reconstruction, r_s [1]

The evaluation of economic processes is based on an analysis of the utility's audited financial statement. It is considered that financial statements and the financial ratio analysis, as a result of the implemented economic policy, provide relevant sources of information regarding the final states of economic processes in some time period. In addition, since sustainability has an undetermined timeframe, it is important for indicators to respect the longevity of the business.

Negative impacts on ecosystems are reflected in environmental component indicators, while social SIs evaluate how end-user needs are met, thus indirectly indicating users' willingness to pay for water services.

The analysis of overall success of water companies in recent years is also based on a variety of non-financial indicators (e.g. non-revenue water indicators) and commonly used indicators include different technical and environmental aspects. Here, the defined institutional indicators focus on utility management and system maintenance.

Numerical expressions for the calculation of SIs, with their target values, are given in Table 2. Expressions for most of the economic indicators are not given since they can be found in literature dealing with analyses of financial statements. The *stability ratio*, as an indicator of net working capital, is calculated as long-term assets divided by the sum of capital and long-term liabilities. The *overall profitability ratio* is calculated as total income divided by total expenditure.

Using the *availability of water resources* indicator was not possible due to the lack of adequate groundwater quantity balance data at the level of the individual WSS. Existing estimates of annual renewable groundwater at the basin level were not considered adequate due to the rough spatial distribution. Therefore, this indicator was not used in this evaluation, but it is certainly necessary to include it if the relevant data exist.

5 Neuro-Fuzzy Model for the Sustainability Evaluation

Given the need for a holistic analysis, thus an analysis of the cause and effect relationship between the processes in the system, a larger number of indicators and their opposing target values, possible incomplete and inaccurate data, the uncertainty in understanding all the processes and their functional relationships in the system, the fuzzy logic and its mathematics imposed as most applicable method for the evaluation of sustainability. One of the purposes of fuzzy systems (models) is an approximation of dynamic systems in which analytical functional relationships are not understandable (Ross 2004). Thus, the nonlinearity and robustness, as inherent characteristics of fuzzy reasoning, are included in the evaluation of sustainability.

The necessary holistic approach is achieved through functional relationships and interactions defined by fuzzy rules. Each fuzzy rule consists of input and output membership functions that transform calculated SIs into the form required for fuzzy mathematics and quantifies the efficiency of the particular process. Since one fuzzy rule can approximate one or a part of a process, complete functional relationships are approximated by a set of fuzzy rules.

First order *Takagi-Sugeno* fuzzy reasoning was chosen, since the *Mamdani* based model is, for this purpose, characterized by a conflicting interpretability-accuracy trade-off and the so-called "curse of dimensionality" due to the greater number of input variables and associated membership functions, resulting in computing issues (Angelov and Xydeas 2005, Yannis and Vassilis 2009, Cordón 2011).

The *Takagi-Sugeno* model also acts much better in modelling dynamic nonlinear systems and optimization processes (Kaur and Kaur 2012). With the assistance of data-mining techniques, this approach allows the adjustment of membership function parameters, taking into

Table 2 Numerical expressions for the calculation of SIs and their target values

Sustainability indicators	Indicator expressions and target values	Indicator components
Water supply reliability α_t [1]	$a_t = \frac{t_z}{365}\left(1 - \frac{n_{in}}{365}\right)$ $a_t \rightarrow 1$	t_z [d] days when required flow and pressure conditions are met, n_{in} [1] water supply interruptions in the system
Independence of water resources k_n [1]	$k_n = \frac{Q_p}{Q_u}$ $k_n \rightarrow 0$	Q_p [m^3] water from other systems, Q_u [m^3] total water introduced into the system
Reliability of water quality α_h [1]	$a_h = \left[\left(\frac{n_p}{n_z}\right) - \left(\frac{n_i}{n_p}\right)\right] \cdot \left[\frac{365 - \left(n_{uz} \cdot \frac{365}{n_p}\right)}{365}\right]$ $a_h \rightarrow 1\left(n_i = 0; n_{uz} = 0; n_p = n_z\right)$	n_p [1] water quality analyses n_z [1] required water quality analyses n_i [1] analyses in which required quality is not satisfied n_{uz} [1] consecutive analyses in which required quality is not satisfied
System vulnerability v_t [1]	$v_t = \frac{N_n}{N_k}$ $v_t \rightarrow 0$	N_n [1] users/connections having interruptions N_k [1] users/connections in the system
Relative efficiency of infrastructure u_i [1]	$u_i = \frac{L_r}{Q_a + L_p}$ $u_i \rightarrow 0$	L_r [m^3] real water losses L_p [m^3] apparent water losses Q_a [m^3] authorized water consumption
Energy independence e_n [1]	$e_n = \frac{E_{vl}}{E_{uk}}$; $e_n \rightarrow 1$	E_{vl} [kWh] self-produced electricity from renewable resources E_{uk} [kWh] total electricity consumption
Water distribution efficiency e_p [1]	$e_p = \frac{\overline{e_{cs}}}{0.7}$; $\overline{e_{cs}} = \frac{\sum_1^n e_{cs}}{n}$ $e_{cs} = \frac{0.2725}{e_s}$; $e_s = \frac{E_{cs,uk}}{Q_{cs,uk}} \cdot \frac{H}{100}$ $e_p \rightarrow 1\left(\begin{array}{l}\text{for over allaverage pumping}\\ \text{system efficiency} \geq 70[\%]\end{array}\right)$	e_s [kWh/m^3 100 m] standardized pumping energy consumption e_{cs} [1] average pumping efficiency $\bar{e}_{cs}$ [1] system average pumping efficiency $E_{cs,uk}$ [kWh] electricity consumption per station $Q_{cs,uk}$ [m^3] pumped water H [m] dynamic operating head
Use of recycled water q_{rc} [1]	$q_{rc} = \frac{Q_{rc}}{Q_u}$; $q_{rc} \rightarrow 1$ (for $q_{rc} \geq 0.85 \rightarrow q_{rc} = 1$)	Q_{rc} [m^3] recycled water
Water resources availability q_{rvr} [1][a]	$q_{rvr} = \frac{Q_u}{Q_o}$; $q_{rvr} \rightarrow 0$	Q_o [m^3] renewable water at the abstraction site
Water resources utilization u_r [1]	$u_r = \frac{L_r}{Q_u}$; $u_r \rightarrow 0$	(IWA *Inefficiency of water resources use* performance indicator)
Chemical sludge production m_c [1]	$m_c = \frac{Q_{mc}}{Q_m}$ $m_c \rightarrow 0$	Q_{mc} [m^3] chemical sludge in water treatment process Q_m [m^3] total sludge production
Sewer disposal of water treatment sludge m_k [1]	$m_k = \frac{q_{mk}}{Q_m}$; $m_k \rightarrow 0$	q_{mk} [m^3] discharged sludge
Utilisation of by-products of water treatment m_i [1]	$m_i = \frac{C_k}{C} + \frac{Q_{m,i}}{Q_m}$; $m_i \rightarrow 1$ (for $m_i \geq 1.0 \rightarrow m_i = 1.0$)	$Q_{m,i}$ [m^3] sludge used for a particular purpose C_k [kg] chemicals reproduced from sludge C [kg] chemicals used in water treatment process

Table 2 (continued)

Sustainability indicators	Indicator expressions and target values	Indicator components
Greenhouse gas emissions k_{GHG} [kg CO_2e/m^3]	$k_{GHG}=\frac{0.17}{GHG}$; $k_{GHG}\to 1$ $\left(0.17\left[\mathrm{kgCO}_{2\mathrm{e/m}^3}\right]\text{taken as target value}\right)$ $GHG=\frac{E_{uk}}{Q_u}\cdot k_1+\sum_i \frac{G_i}{Q_u}\cdot k_i$	GHG [kg CO_2e/m^3] total greenhouse gas emissions calculated with conversion factors for electricity (k_1) and petroleum products (k_i) G_i [l] used gasoline and diesel fuel
Water supply network coverage p [1]	$p=\frac{N_p}{N_{uk}}$; $p\to 1$	N_p [1] residents with the possibility of connecting to the water network N_{uk} [1] residents in the utility service area
Complaints related to quality of service z_u [1]	$z_u=\frac{U}{N_{p,uk}}$; $z_u\to 0$	U [1] complaints regarding the quality of service $N_{p,uk}$ [1] water supply connections
Water pricing policy c_v [1]	$c_v=\frac{p_{cv}}{c_{vt}}$; $c_v\to 1$	p_{cv} [euro/m^3] production and distribution costs of 1 [m^3] of water including utility costs c_{vt} [euro/m^3] market price of 1 [m^3]
Cases of illness caused by poor water quality b [1]	$b\to 0$ (for $b\geq 1\to b=1.0$)	b [1] cases of illness
Level of informing end users i [1]	$i=\frac{I}{50}$; $i\to 1$ (for $i\geq 1.0\to i=1.0$)	I [1] parameters regularly published by the utility; 50 taken as a target value
Involvement of end users n_r [1]	$n_r=\frac{N_{r,t}}{2}$; $n_r\to 1$ $\left(\text{for } N_{r,t}\geq 1.0\to N_{r,t}=1.0\right)$	$N_{r,t}$ [1] publicly held forums/workshops 2 taken as a minimum value
Benchmarking programme participation, bp [1], or utility internal analysis bi [1]	$bp=\frac{b_n}{100}$; $bi=\frac{b_n}{100}$ $bp\to 1$; $bi\to 1$ (for $b\geq 1.0\ \to\ b=1.0$)	b_n [1] indicators analysed by the utility 100 taken as a target value
Water consumption control programme p_s [1]	$p_s\geq 1$ or $p_s=\frac{A}{N_{p,uk}}$; $p_s\to 1$	p_s [1] consumption control programmes A [1] number of water saving devices; can be used in the case of the absence of water consumption control programmes (one device per household as target)
Employee retraining t_z [1]	$t_z=\frac{Z_t}{40}\cdot\frac{n}{n_{z,uk}}$ (for $t_z\geq 1.0\to t_z=1.0$)	n [1] employees who participated in additional training Z_t [h/employee] average educational hours (40 h taken as a minimum value) $n_{z,uk}$ [1] total number of employees
Unbilled consumption p_l [1]	$p_l=\frac{P_n+L_p}{Q_n}$; $p_l\to 0$	P_n [m^3] unbilled authorized consumption Q_n [m^3] total revenue water
Non revenue water q_{nv} [1]	$q_{nv}=\frac{L_r+L_p+P_n}{Q_u}$; $q_{nv}\to 0$	Achievable target value for q_{nv} taken as 10 [%] (for $q_{nv}\leq 0.1\to q_{nv}=0.0$)
Billed water metering m_p [1]	$m_p=\left(1+\frac{V_{s,a}}{N_{p,uk}}\right)\cdot\left(\frac{V_s}{N_{p,uk}}\right)$; $m_p\to 2$ $\left(m_{p,min}\to 1;\text{for } m_p>1.0\to m_p=1.0\right)$	V_s [1] water meters in the system $V_{s,a}$ [1] automated water meters in the system

Table 2 (continued)

Sustainability indicators	Indicator expressions and target values	Indicator components
Work-related injuries k_o [1]	$k_o = \frac{1}{1.15 \cdot o}$ $k_o \to 1$; (for $o = 0; k_o = 1$)	o [1] work-related injuries that required medical assistance
Elimination of water system failures k [1]	$k = \frac{0.25}{T}$ $k \to 1$; (for $T < 0.25; k = 1$)	T [d] average duration of recovery from failure
Water system reconstruction r_s [1]	$r_s = \frac{R}{I_m}$; $r_s \to 0$	R [euro] costs for the system reconstruction I_m [euro] the value of fixed assets related to buildings, equipment, tools and inventory

[a] Not included in the analysis due to the lack of relevant data

account all the characteristics of the analysed system and still providing continuity of the output surface (result) (Van Leekwijck and Kerre 1999).

The purpose of data mining is the extraction of unknown process interactions from the system behaviour pattern (input SIs combinations) for which the result is known, thus for which the system is well represented. For this purpose, an *artificial neural network* is used since its various adaptive capabilities adjust the input and output membership functions, seeking to mimic the required system characteristics in the best possible manner. This *Adaptive Neuro Fuzzy Inference System (ANFIS)*, created in MathWorks Matlab software, release 2014a, computes the result for different combinations of input variables not included in the training set.

The data matrix for neural network training is formed with columns representing input variables (SIs) and rows containing associated values. The last column of the matrix represents known results of the input indicator combinations. For input variables having the worst values (usually 0.0 or 1.0, depending on the indicator), the result is a value that represents the maximum distance from a sustainable state. The result of that combination is then equal to 0. The same applies for a combination with the highest indicator values for which the final result is equal to 1.0. Also, for a combination in which all indicators are 10% away from the most adverse state, the result is equal to 0.1. A 20% distance from the worst state would result with the value equal to 0.2, and so on.

Since evaluation is based on a quasi-strong sustainability concept, additional combinations taking into account strict environmental criteria were created. These combinations result in restricting values for the *environmental criteria* and the final *index* if the input variables (environmental SIs and the environmental component) have low values.

If any of the environmental indicators has a value equal to 0 and all the other environmental indicators have maximum values, the maximum possible result would be 0.3 for the criterion of *effectiveness of water resources use* and 0.35 for the criterion of *minimization of by-products*. The same principle was used for the sustainability index aggregation for which restrictions were used only for the environmental component with a limiting value of 0.35. Other combinations with a linear distribution from 0 to 0.3 (0.35) were created in the same way as previously explained. The values of 0.3 and 0.35 were arbitrarily chosen and can be changed in order to reflect a higher weight in the result for a low environmental component and indicator values.

Training is performed as *Batch Training* through a 5-layered neural network with a sigmoid function as a differentiable activation function for processing elements. The neural network adjusts the parameters of input membership and output linear functions in order to adapt the ANFIS model to the learning data set.

The goal of training is to obtain results for those SIs combinations for which it is difficult to comprehend (calculate) the distance from a sustainable state due to the different orientation of indicators (increasing and decreasing values not equally distributed between the lowest and highest value) and the imposed environmental restrictions. Figure 2 shows the results of the network training process whose graphical presentation is limited due to multidimensionality.

From each training matrix, two rows were omitted as they are used to evaluate the training process and to assess the training error. All training results showed negligible learning error and a negligible difference for the test sample values. It was concluded that a result can be reliably determined for a specific combination of SIs.

ANFIS parameters (fuzzy operators, neural network training algorithms and corresponding parameters, the defuzzification method) were tested on the preliminary model with 5 input variables.

The optimization of the preliminary model is based on the continuity and monotonic increase of the codomain criteria. The analysis showed that the *Subtractive Clustering* method better meets these requirements. This method divides the training data domain (input space) into a certain number of clusters (membership functions) that represents an approximation of local nearby values to a single group, that is, to one fuzzy rule. The shape of the input membership function is limited to a *Gaussian function* which is defined by the mean domain group parameter (where the function has the largest membership of a group) and variance.

The number of input membership functions, together with their two parameters, is determined by the arbitrary adjustment of cluster algorithm parameters. The number of fuzzy rules and clusters were determined as the minimum needed clusters for which a continuity and monotonic increase was achieved, also taking into account the convergence of the final result. The difference that was no bigger than 0.015 between the minimum needed clusters and 200 clusters (80 clusters for 2 input variables) was taken as the reference value.

It was also determined that the *AND* neuron type (as a logical operation), the *Hybrid training algorithm* (as a network training algorithm) and the *weighted average* (as a defuzzification method) better adapt to the set requirements. The model optimization resulted in 7 membership functions for 2 and 17 membership functions for 4 and 5 input variables.

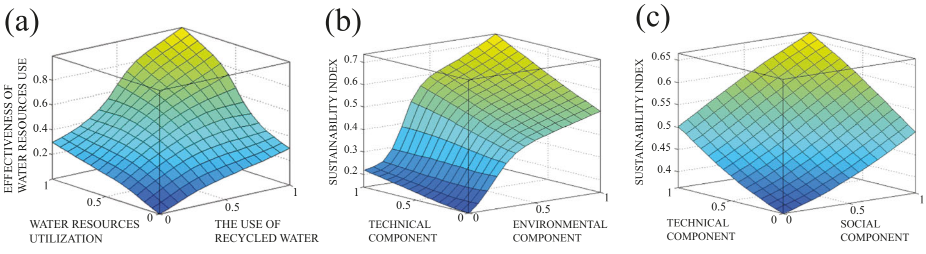

Fig. 2 Neural network training results for: (**a**) environmental criteria; (**b**) sustainability index with environmental restriction; (**c**) sustainability index for components other than environmental

Eventually, the preliminary model was thoroughly tested and it was concluded that it meets all of the criteria. Also, results showed that the imposed restrictions are reflected for low environmental SIs and that for any combination of input values the final result shows the distance from the maximum possible value.

Although the *Subtractive Clustering* based ANFIS model can handle high-dimensional problems with many input variables, in order to evaluate each sustainability criterion and component, a nested hierarchy modelling approach was used. In this way, the decomposition of sustainability components was done so that each criterion is evaluated with a separate model (input SIs according to Table 1).

6 Data Gathering and Processing of Indicators

Data required for the calculation of indicators, according to Table 2, were gathered through a digital survey questionnaire that was distributed to all utility companies in Croatia. However, only 20 utilities voluntarily participated in the research. Although it had no effect, the utilities were able to be grouped by the amounts of extracted water so that both small and large systems were analysed. The questionnaire (with instructions on how to fill it) required only numerical values. It was designed so that certain data are requested a few times in slightly modified form in order to determine the consistency and reliability of the gathered data. The period of analysis included 2011 and 2012. Data double-checking was done according to the data gathered from the databases of official agencies and organizations to which the utilities are obliged to submit different reports containing the required data. For each analysed system, the rating of data reliability was done according to which three utilities were excluded from the analysis due to data inconsistencies.

7 Results and Discussion

For each sustainability component, indicators were calculated according to the expressions in Table 2 and used as model inputs for sustainability criteria evaluation. The results for 2012 are shown in Table 3.

The obtained criteria results, within a particular component, are aggregated into a *sub-index*, thereby quantifying that component of sustainability. The sub-index represents a measure of distance that shows how far a certain component is from the best result. Technical, social and institutional components are calculated as an average value of two criteria. The economic component is equal to the economic criterion and the environmental component is calculated with the restricting ANFIS model for two input variables.

After the performance of each sustainability component is calculated, the overall result is calculated by the additional restricting aggregation ANFIS model for which five sub-indices are used as input variables, Fig. 3.

The final result is a numeric value, ranging from 0.0 to 1.0, which determines the distance from a state previously defined as sustainable, meaning that this numeric value determines the sustainability index. The sustainability index equal to 1.0 represents a sustainable state of the system, while the index equal to 0.0 represents the state of the system farthest from the sustainable.

Table 3 Sustainability criteria results for 17 analysed water supply systems/utilities for 2012

2012	Sustainability criteria								
Water supply system / Utility (city)	Technical component		Economic component	Environmental component		Social component		Institutional component	
	Operational effectiveness	Energy use effectiveness	Economic effectiveness	Effectiveness of water resources use	Minimisation of by-products	Meeting end-user needs	Informing and involvement of end users	Management effectiveness	Systems maintenance effectiveness
1. Komunalac (Bjelovar)	0.90	0.40	0.63	0.18	0.32	0.99	0.26	0.09	0.68
2. KD Cabranka (Cabar)	0.86	0.48	0.34	0.20	0.08	0.98	0.09	0.45	0.76
3. Medimurske vode (Cakovec)	0.85	0.33	0.42	0.19	0.81	0.80	0.73	0.43	0.84
4. Komunalac Glina (Glina)	0.82	0.25	0.44	0.10	0.84	0.80	0.13	0.03	0.48
5. Komunalac (Koprivnica)	0.93	0.39	0.25	0.23	0.29	0.97	0.48	0.42	0.55
6. Komunalac (Hrv. Kostajnica)	0.90	0.20	0.38	0.18	0.29	0.95	0.16	0.02	0.72
7. Krakom (Krapina)	0.94	0.22	0.51	0.20	0.19	0.88	0.16	0.40	0.49
8. Komunalije (Novalja)	0.76	0.48	0.62	0.21	0.90	0.94	0.13	0.42	0.78
9. Novokom (Novska)	0.87	0.09	0.57	0.22	0.49	1.00	0.05	0.16	0.73
10. Komunalije (Ilok)	0.91	0.20	0.52	0.19	0.13	0.82	0.13	0.42	0.73
11. Vodovod Osijek (Osijek)	0.94	0.39	0.49	0.17	0.09	0.96	0.33	0.24	0.49
12. Papuk (Orahovica)	0.78	0.40	0.49	0.20	0.98	0.82	0.20	0.33	0.53
13. Komunalac (Pakrac)	0.79	0.13	0.68	0.11	0.07	0.92	0.52	0.17	0.75
14. Vodovod i odvodnja (Sibenik)	0.66	0.36	0.54	0.16	0.83	0.92	0.28	0.11	0.57
15. VG Vodoopskrba (Velika Gorica)	0.86	0.17	0.63	0.17	1.00	0.93	0.20	0.14	0.54
16. VVK (Vinkovci)	0.77	0.40	0.46	0.22	0.93	0.94	0.83	0.15	0.49
17. Vodovod grada Vukovara (Vukovar)	0.87	0.37	0.59	0.16	0.39	0.88	0.24	0.12	0.54

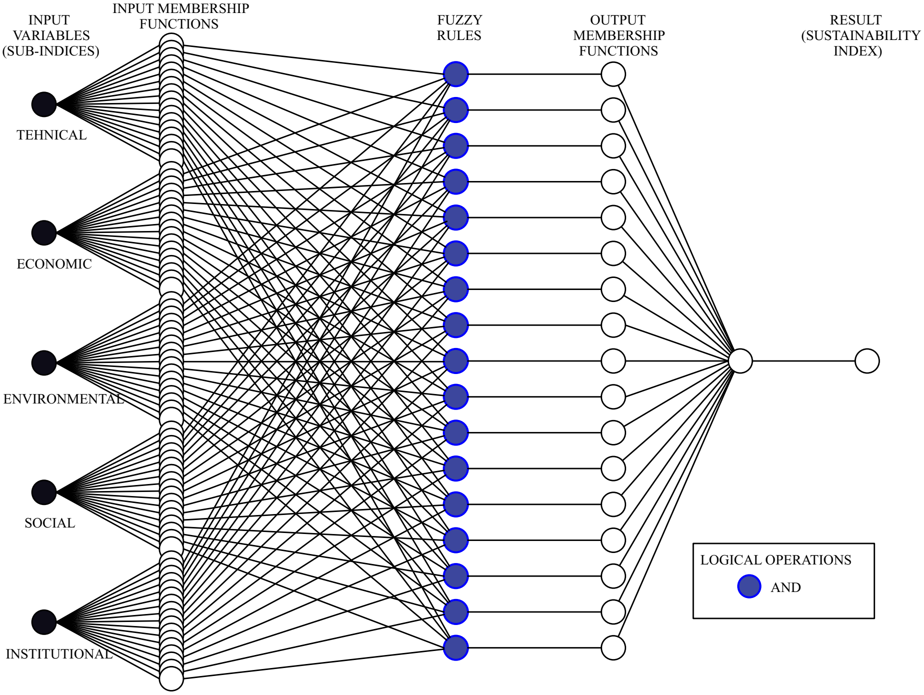

Fig. 3 The structure of the ANFIS model for the calculation of the sustainability index

The sustainability index for 17 WSSs was calculated for 2011 and 2012. The result for 2012 is shown in Table 4.

The influence of the environmental component is visible for three WSSs (Cabar, Osijek and Pakrac). Rather high values of other components are reduced in the final aggregation due to a low environmental component value. However, if the environmental component has a sufficiently good value, as for the Vinkovci WSS, then a low value for a component other than the environmental component, such as the institutional component, for example, can be compensated for by some other high component value, like the social component, as in this case. In this way the quasi-strong sustainability concept is reflected in the evaluation model.

8 Conclusion

The paper presents the methodological framework for quantifying sustainability of WSSs. The quantification is based on the use of SIs and their aggregation into the sustainability index. The aggregation is performed through the joint fuzzy logic and neural network model, while it relies on the originally proposed concept of quasi strong sustainability. Likewise, this framework represents a novelty in the sustainability analysis of some urban water system.

Also, the original definition of sustainable WSS was proposed, where the sustainability is defined as a condition in which the utility is able to control all the processes in the system and is not dependent on resources from natural environment.

Table 4 Sustainability sub-indices and indices for 17 analysed water supply systems/utilities for 2012

2012	Sustainability subindex and index values					
Water supply system / Utility (city)	Technical component	Economic component	Environmental component	Social component	Institutional component	Sustainability index
1. Komunalac (Bjelovar)	0.65	0.63	0.24	0.62	0.38	0.32
2. KD Cabranka (Cabar)	0.67	0.34	0.11	0.53	0.60	0.21
3. Medimurske vode (Cakovec)	0.59	0.42	0.38	0.76	0.63	0.50
4. Komunalac Glina (Glina)	0.53	0.44	0.34	0.46	0.25	0.38
5. Komunalac (Koprivnica)	0.66	0.25	0.25	0.73	0.49	0.34
6. Komunalac (Hrv. Kostajnica)	0.55	0.38	0.22	0.56	0.37	0.29
7. Krakom (Krapina)	0.58	0.51	0.17	0.52	0.44	0.26
8. Komunalije (Novalja)	0.62	0.62	0.41	0.53	0.60	0.52
9. Novokom (Novska)	0.48	0.57	0.33	0.52	0.45	0.42
10. Komunalije (Ilok)	0.56	0.52	0.14	0.47	0.58	0.23
11. Vodovod Osijek (Osijek)	0.66	0.49	0.10	0.64	0.37	0.21
12. Papuk (Orahovica)	0.59	0.49	0.43	0.51	0.43	0.48
13. Komunalac (Pakrac)	0.46	0.68	0.08	0.72	0.46	0.22
14. Vodovod i odvodnja (Sibenik)	0.51	0.54	0.37	0.60	0.34	0.44
15. VG Vodoopskrba (Velika Gorica)	0.51	0.63	0.41	0.57	0.34	0.48
16. VVK (Vinkovci)	0.58	0.46	0.43	0.89	0.32	0.52
17. Vodovod grada Vukovara (Vukovar)	0.62	0.59	0.26	0.56	0.33	0.35

The list of 35 indicators divided in 5 components (dimensions) of sustainability was proposed. Consequently, for most indicators the original definitions were given. Finally, by using the created model, the sustainability was quantified for 17 analysed WSSs.

According to the results, it can be concluded that the fuzzy logic is appropriate method for the evaluation of WSS sustainability, and that the final result represents the sustainability index, showing how far the analysed system is from being sustainable.

Also, although the proposed framework shows a very good applicability in this topic, due to a multitude of possible parameters, fuzzy operators and neural network algorithms, it is necessary to understand the problem. Otherwise, the inappropriate use of fuzzy logic or neural network can lead to false and mislead results.

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