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Identification of priority NRW-reduction measures using a decision support system

Primož Banovec*, Ajda Cilenšek, Matej Cerk

Faculty of Civil Engineering and Geodesy, University of Ljubljana, 1000 Ljubljana, Slovenia, Tel. +386 1 476 85 00; Fax: +386 1 425 0681; emails: primoz.banovec@fgg.uni-lj.si (P. Banovec), ajda.cilensek@fgg.uni-lj.si (A. Cilenšek), matej.cerk@fgg.uni-lj.si (M. Cerk)

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ABSTRACT

Non-revenue water (NRW) defined by the standard International Water Association (IWA) terminology is an important issue in the management of water supply systems (WSS). Its main component, water loss, is traditionally challenged by the managers of the WSS. The issue of NRW reduction is gaining in importance due to several impact factors: ageing WSS, increased energy costs and also new requirements set by the Water Framework Directive (WFD). Beside the conventional water loss requirements and indicators, WFD sets additional requirements defined by the objective status of water bodies. The directive was addressed by the WATERLOSS EU-MED project, within which a decision support system (DSS) for the induction of NRW-reduction measures was developed. The DSS targets beyond the standard benchmarking approaches with the evaluation of indicators that serve for the identification of necessary measures. In the process of DSS development, three key components were connected in operative DSS: (1) system of indicators that is based upon the modified IWA benchmarking system; (2) comprehensive classification of all identified NRW-reduction measures; and (3) a rule-based system that connects both and induces priority measures on the basis of evaluated indicators. In the article, all three components will be presented with special emphasis on the induction process. The induction process is based upon multidimensional clustering and embedded expert knowledge.

Keywords: Water supply systems; Non revenue water; Water losses; Expert decision support system; Performance indicators

1. Introduction

Management of water losses is a common task for which most water-utility managers are struggling with. High water losses usually result in limited availability of water as a resource, increased Operation and Management (O&M) costs of Water Supply Systems (WSS) and increased pressure on water resources. This could potentially lead to a limited or intermittent water supply, which could affect water quality and even result in adverse effects on human health. The issue of water losses and relative non-revenue water

*Corresponding author.

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(NRW) was recognized as a priority in the on-going WATERLOSS EU-MED project, which has several aims. A specific aim is also to bridge the gap between the science community that provides state-of-the-art approaches and technologies and the end users, who are often administrations and utility managers with limited contact with advanced approaches and tools for the reduction of NRW. The definition of NRW was adopted from the International Water Association (IWA) [1]. The reason for this EU-MED priority is also recognized in the identified gap between the WSS management process and the water resources management process in the Mediterranean region.

The process of evaluating water losses begins with establishing the water balance and the broad set of variables/indicators set by the IWA [1]. This is recognized as a firm starting point for any examination in this domain. For further steps in the analytical/auditing process, different tools can be applied to support the evaluation process. For this purpose, several audit tools have been developed and are used to assess the IWA water balance and the IWA database of Performance Indicators: BENCHLEAK/BENCHLOSS [2], AQUA LITE [3] and AWWA WLCC [4]. All the listed water audit software tools have one thing in common—they help assess water balance and NRW. On the other hand, they do not provide as an output a suggestion of measures for reducing NRW. They are, therefore, an important tool, which, however, only partially addresses the complex planning—implementation—monitoring management cycle that should be part of a comprehensive decision support system (DSS). The aim of the WATERLOSS EU-MED project was to go beyond the existing auditing tools and also provide guidelines for the user toward a limited set of priority measures resulting in the reduction of NRW, functioning as a DSS [5].

2. DSS framework

DSS theory provides support in the decision-making process under uncertainty and imprecision [6]. Often, this support is necessary because of a vast amount of data and information and limitations of the human mind in finding specific rules in data-sets. Advancing computer technology plays a major role, enabling efficient and effective management of data and concepts. On the other hand, computer technology provides improved user interaction on all stages of the DSS process—data input, data evaluation and analysis and preparation and evaluation of results including web-based DSS [7], which was also the aim of the WATERLOSS project. A more advanced use of a DSS is also related to the concepts of artificial intelligence. WATERLOSS DSS could be positioned in the knowledge-base or knowledge-driven DSS (Fig. 1).

Water utility managers usually favour the use of the DSS. With the INSPIRE directive in place by the EU [8], all utility managers are obliged to use some kind of a GIS system for the asset management (database data-driven DSS), which is used as a DSS tool. Nevertheless, the uncertainty associated with the decision-making process, including GIS-related asset management, is often neglected. Hydraulic modelling of the WSS provides an example of the model-driven DSS. The framework for the development of the DSS is based on the decision-making probabilistic theory described by Haimes [9]. The same conceptual framework was also used for structuring the concept of the knowledge-driven WATERLOSS DSS. As soon as the DSS was developed, it was recognized that many components necessary for the supported decision-making process are missing [10,11], which is why an adequately supported DSS could not be developed. Instead, work on the definition of decision nodes and other components necessary for DSS was performed. The adequate definition of the decision tree, presented in Fig. 2, was necessary in order to adapt it to the decision-making process, aimed at the reduction of NRW in WSS. In such a framework, it is clear that the decision node could be described as a dilemma of the decision-maker (i.e. water-utility manager) on how to reduce the NRW. He is the one who decides upon different alternatives which lead towards the reduction of NRW.

The *alternatives* are, therefore, different possible measures, the implementation of which would result in the reduction of NRW. They will be discussed later in the section "Classification of the NRW-reduction measures". *State* is the actual state of the WSS. The description of the state of the WSS is important in order to identify the effects of implementing different alternatives (measures). To standardize the DSS, the description of the state of the WSS was defined [12] by the variables set by the IWA [13]. Using the standardized (IWA) approach [14–16] for the definition of the state of the WSS was almost imperative in order to facilitate the use of the DSS by different utilities involved in the project and its later potential use in the process of capitalization of the project results. The *probability node* defines the probabilistic relationship between the alternative state and consequence. In the case of WSSs and relative NRW, the probability node should define the effect of the application of a specific alternative—measure for the reduction of NRW. It should, therefore, for example, define the relationship between the reduction of NRW and specific measures—such as pressure reduction, pipe rehabilitation and increased frequency of metre replacements. This

Dominant DSS component	User group: Internal, external	Purpose: General, specific	Enabling technology
Communications-communications driven DSS	Internal teams, now expanding	Conduct a meeting, Bulleting board, Help users collaborate	Web or Client/server
Database Data-driven DSS	Managers, staff, now suppliers	Query a data Warehouse	Main Frame, Client/Server, Web
Document base, knowledge driven DSS	Specialists and user groups is expanding	Search web pages, Find documents	Web
Knowledge base, knowledge driven DSS	Internal users, now customers	Management advice, Choose product	Client/Server, Web
Models - Model driven DSS	Managers and staff, now customers	Crew scheduling, decision analysis	Stand-alone PC

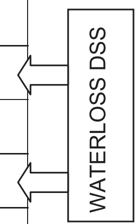

Fig. 1. Key: Expanded DSS framework (according to [6]—with the positioning of the WATERLOSS DSS in two main DSS components).

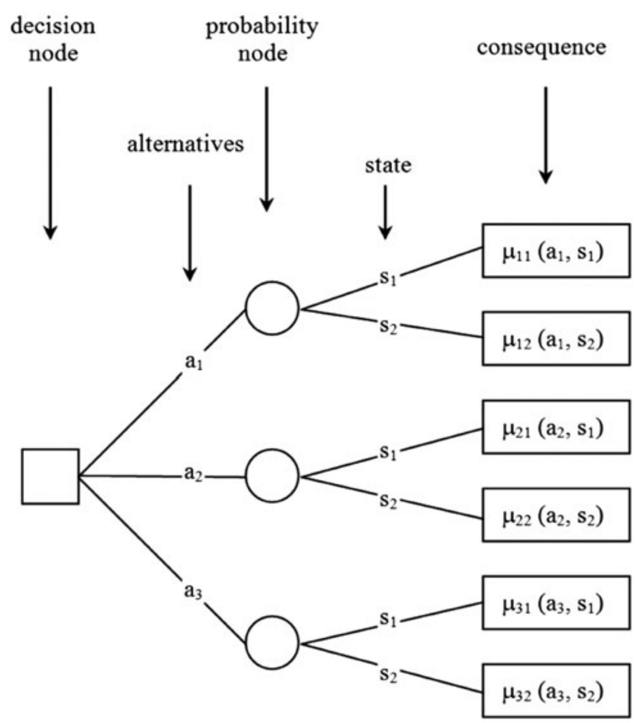

Fig. 2. Key elements describing the probabilistic theory of decision-making used for the WATERLOSS DSS.

relationship should be defined in a probabilistic framework, taking into consideration different (probabilistic) consequences (NRW reduction) of a specific applied measure. In such a definition of the decision-making process, the basic decision-making dilemma: "Which is the most suitable NRW-reduction measure for my WSS?" could be encoded into the standardized DSS, in the future, also taking into account the probabilistic aspects (uncertainty) of the decision. Different authors [17–19] have already done some work in this field. The aims of the developed DSS were: (1) supportive—supporting the decision-makers of water utilities and supervising administrations in adequate decision-making and (2) educative—educating the same about the possible measures and their effects.

2.1. Limitations and development process

In the development of the described DSS, several bottlenecks were identified and attempts were made to resolve them. They are related mostly to the fact that there was only limited effort in the professional community applied so far in addressing this process in a systematic way. In the conclusions and discussion sections, possible reasons for this will be analysed. For the functioning of the DSS, several components were developed aiming at the operationalization of the DSS process described in the previous paragraph.

Reporting system—for a standardized description of any WSS from the point of view of NRW, large sets of variables are required. Development of the indicators necessary to describe the WSS was a part of another task group in the WATERLOSS project. It resulted in the selection of variables necessary for the identification of key indicators [20,21]. Within the reporting system, an internet-based application was developed enabling upload and basic-level evaluation of these variables. The basic window for the overview of the reported results is shown in Fig. 3.

The reporting system serves as a basic entry point for each user (i.e. water utility) as they have to provide key information on the WSS under evaluation in the decision-making process. At the initial stage of the project, a reporting system was developed for the full set of IWA variables, but was later abandoned as it required many variables that were not directly connected to the decision-making process related to NRW reduction. Development of the reporting system in the framework of the DSS was necessary for several

Fig. 3. DSS NRW reduction reporting system showing central internet application for the upload of the data (variables) on analysed WSSs.

reasons. The main reason was to standardize the input data for the DSS evaluation process. It also provides a framework for the open use of the tool after the completion of the project, where it will be possible for users to enter the information on their system without a mediator and to use a DSS system based upon their own data. The reporting system, based upon the annual upload of large data-sets, also allows simplified version of the input and relative evaluation based upon the corrected data on the WSS.

Classification of the NRW-reduction measures—Adequate classification of the NRW-reduction measures was a key element for the operation of the DSS. In the decision-making process, possible measures are defined as alternatives. In order to have an effective DSS, it was necessary to (1) provide the description of all possible NRW-reduction measures and (2) encode the defined measures in an effective way into the DSS tool. The definition of the NRW-reduction measures was performed in component 4.1 of the WATERLOSS project. It was defined in a combined bottom-up (definition of any possible measures that could contribute to NRW reduction) and top-down approach (guided by the components of the water balance of WSS). During the process of defining NRW-reduction measures, it was recognized that any specific classification of the NRW-reduction measures could not be used. A review of literature, describing approaches towards NRW reduction [22–32], was made and a new classification was developed, which is structured (using top-down approach) in such a way as to facilitate its implementation in the DSS.

An important feature of the classification of the NRW-reduction measures is that it is hierarchical with two hierarchical levels: first level, describing a strategic approach to measures and second level, describing the operational measures. A third level could potentially be added, describing the technological approach suggested by different (competitive) technology providers. The strategic approach is defined by 48 classes and operational level is defined by 175 classes. The aim of the DSS was to provide the decision-making platform for the selection of prioritized measures on the level of strategic approach to measures. Number of classes in each category is subject to changes relative to the development of the DSS. The classification of measures on both levels was integrated into the DSS with an aim that the DSS would support the user in the selection of strategic approach to measures. Lower level classification—operational measures, are shown as potential operational measures, which are assigned to a specific strategic level. The nature of the operational measures is very specific in terms of their regional and local applicability, cost, timeframe, institutional complexity, etc.

2.2. *Definition of probability nodes*

Definition of probability nodes was an essential element for the effective operation of the DSS. In the probabilistic theory, which defines the framework, the probabilistic nodes should be defined by the probability of the alternative based upon the state of different indicators of the WSS and relative consequence. The probabilistic framework should be defined by the Bayesian statistics [33,34] and could, as such, be used quantitatively in the decision-making process with the DSS. Unfortunately, there is no or very limited experience-based information available on the consequences —reduction of NRW in WSS, which would result from specific measures applied in a controlled environment in actual WSSs. This would provide information on the probability of a consequence of a specific measure applied for a specific set of indicators describing the WSS. Main identified reasons for the absence of this information are:

- Combination of measures that result in NRW reduction—utility managers usually apply different measures for NRW reduction at the same time. It is quite difficult to assess the effect of a single applied measure, and specific studies to identify this are usually not performed.
- Absence of a systematic collection of experiences with the application of NRW-reduction measures. Country-specific and sector-specific reporting systems usually collect information on regular O&M of WSS, and thus provide the function of general or specific benchmarking tools. There is no reporting and evaluation framework for the evaluation of the effects of specific NRW-reduction measures on specific WSS, which would provide this information.
- Regional and country-specific measures and experiences—management of WSS and target management of NRW—are often closely related to regional specific conditions. Some concepts (i.e. rooftop reservoirs, intermittent supply and limitation of water resources) are very specific and do not provide a framework for the general comparison of approaches.

To overcome these limitations, two approaches were developed within the WATERLOSS project:

- Definition of specific threshold values in the decision-making path—the selection of measures is, therefore, not made in the probabilistic way but is set on the specific variable or indicator from the reporting system with a possibility to define threshold levels of the variable (possibility country specific and sector specific).
- Reporting system for the development of registry of WSS-specific experiences in the application of different NRW-reduction measures and resulting effects (water reduced).

The implementation of the reporting system for the applied NRW-reduction measures and their efficiency is considered as a learning tool, which in the long run enables the system to use actual NRW-reduction efficiency data instead of general threshold values (Fig. 4).

3. DSS tool for the reduction of NRW

The developed DSS tool supports the decision-making process described above, where the main

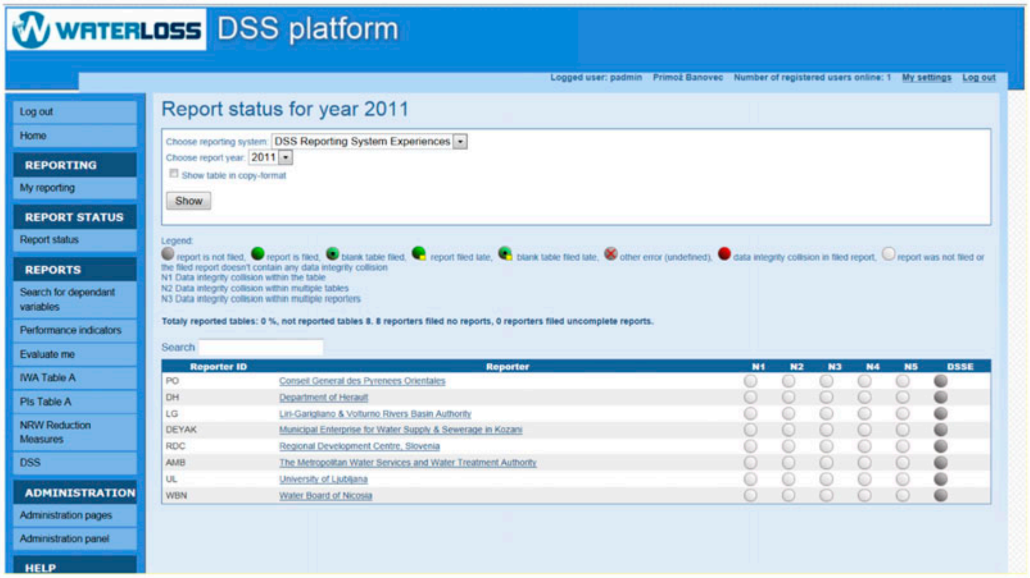

Fig. 4. Reporting system for the implemented NRW-reduction measures and their efficiencies.

decision dilemma lies in the question “which is the most appropriate NRW-reduction measure for my WSS”. For this purpose, a decision-making tree was developed that combines the expert knowledge in NRW reduction obtained from the literature and professionals involved in the WATERLOSS project with the developed classification of measures. DSS supports the decision-making process defined by the components of water balance with the identification of components and sub-components of the water balance that are, according to the available data on WSS (see reporting system), of key importance regarding the prioritized selection of NRW-reduction measures. For each decision node, the indicators that are calculated from the variables reported are used in the reporting system for the WSS under consideration. It is, therefore, quite important to have sufficient and reliable information on the WSS, which is, of course, a prerequisite for any decision-making process. A specific decision pathway, therefore, always provides an option that not enough data are available for the decision-making process and suggests that more thorough data collection for the specific WSS should be performed in order to support the decision-making process (Fig. 5).

The decision nodes verify the decision variables (taken from the reporting system) and provide the decision based upon the threshold levels implying the priority for the selection of a specific alternative as priority measure. The threshold levels are defined from literature where it is available (i.e. an important threshold is the ILI—infrastructure leakage index), but most of the thresholds used are not yet defined in the professional literature. In such cases, expert evaluation was used based on expert knowledge (defined in the WATERLOSS deliverable 4.1—IRSTEA). Users of the DSS can also define their own set of threshold values mirroring regional and national-specific conditions. Fig. 6 presents the main modules applied in the web-based WATERLOSS DSS.

4. Application of the DSS

Use of the DSS was tested for different WSSs with WSS of Velenje being the first reality check and experience-based example. Water utility of Velenje provides public service for the Šaleška valley in the Republic of Slovenia. They manage three WSS with total population of 43,000 inhabitants. It annually supplies approximately 3.000.000 m^3 of drinking water. First analyses show that NWR amounts to 34% and water losses to 30%, respectively. Figs. 7–9 show the use of the WATERLOSS DSS on the example of Velenje WSS. Fig. 7 presents the key data on the specific WSS—which in the perspective of NRW reduction is the actual water balance. Based upon the defined decision tree and threshold values, the system analyses the reported data of specific WSS and indicates the pathway, which leads towards the selection of prioritized measures. First step of the supported decision-making process is shown in Fig. 8.

As seen in Fig. 8, the DSS recognizes the role of the NRW as high priority. Other information on this

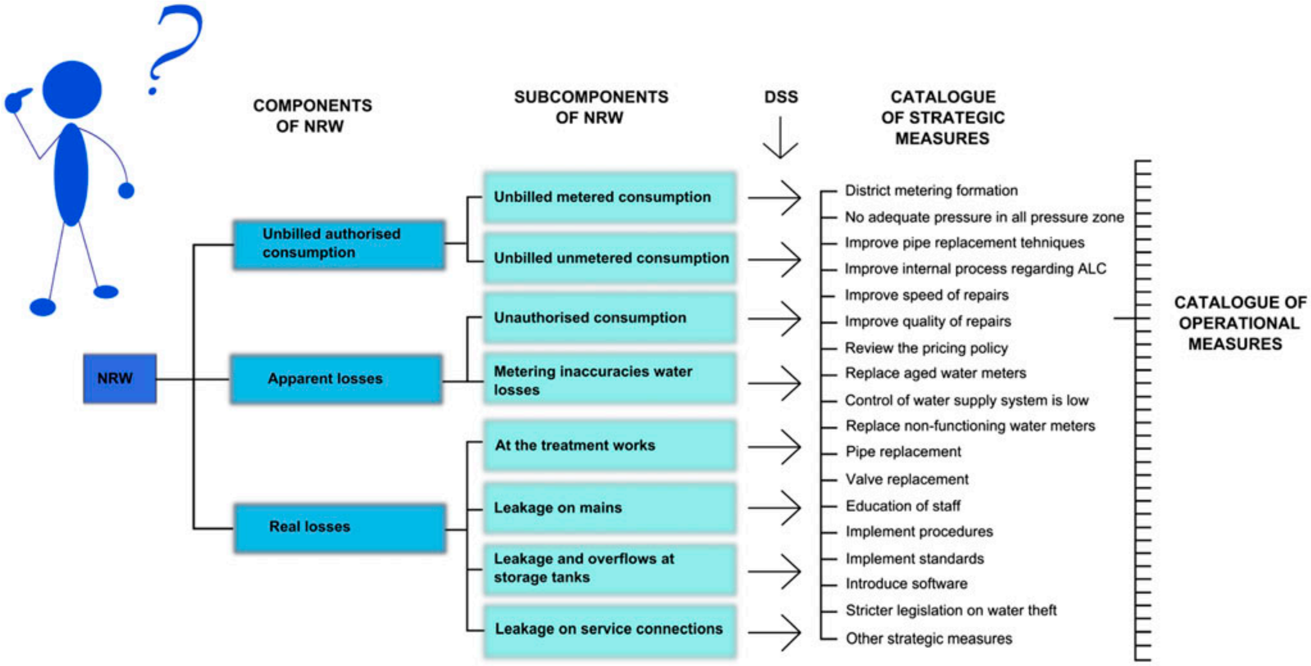

Fig. 5. Conceptual approach to the definition of the DSS—bridging the gap between the main indicators (water balance) and induction of prioritized NRW-reduction measures.

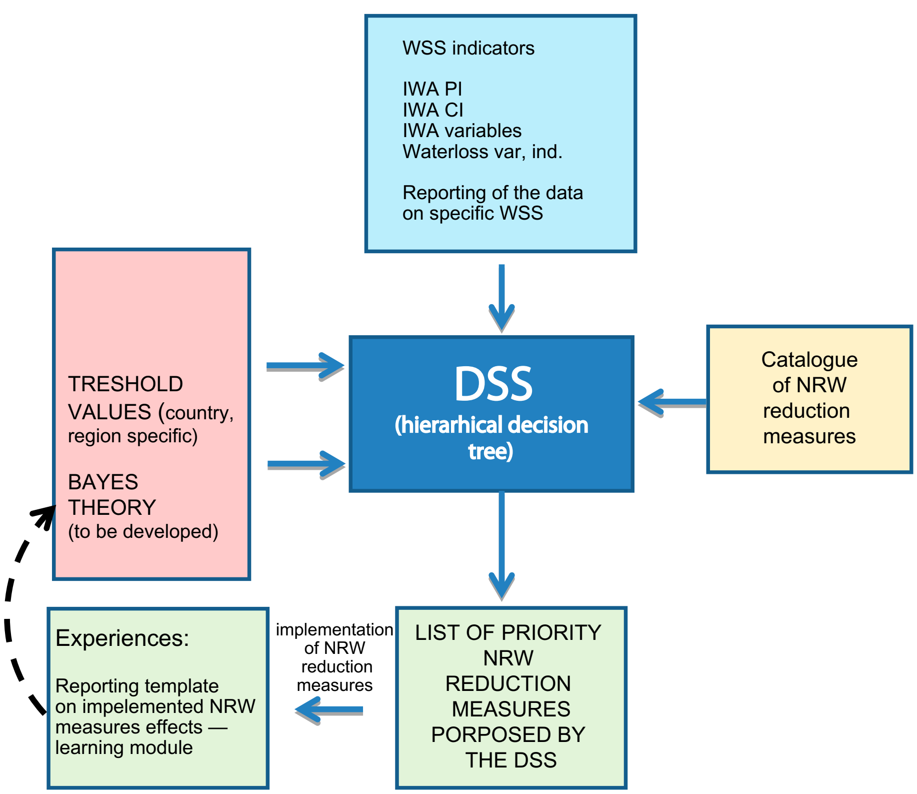

Fig. 6. Modsules of the WATERLOSS DSS.

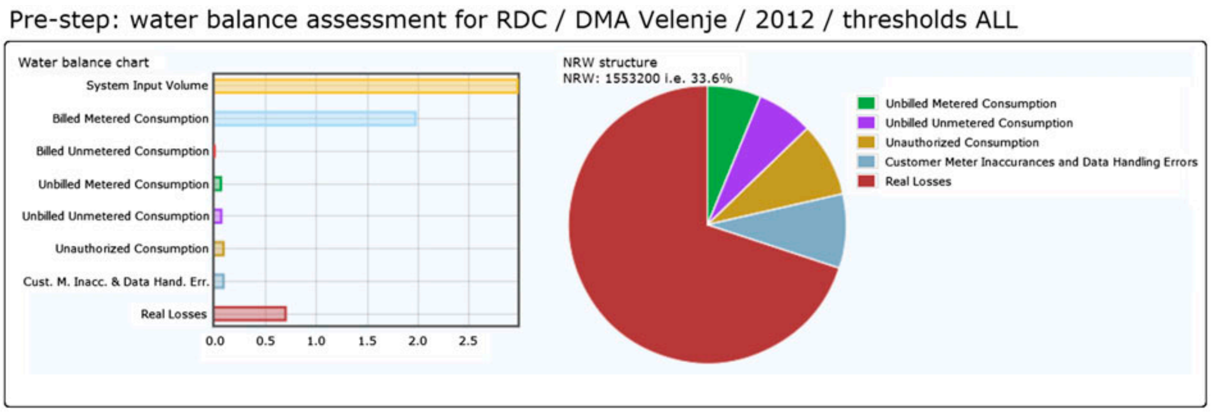

Fig. 7. Overview of the water balance for the specific WSS under evaluation of the DSS—reported data overview.

specific step is listed under suggestions. With a click on the suggested decision pathway (NRW is not low), the next window appears, which is shown in Fig. 9.

When the decision process propagating from the initial node (Fig. 8) reaches one of the final branches of the decision-making process (tree), defined as strategic group of measures, the DSS indicates possible operational NRW-reduction measures, related to this strategic group of measures. A list of the operational measures at the node is then shown to the user indicating, beside the measure description, also the qualitative assessment of the measure from following viewpoints: relative importance of the NRW-reduction measure, timeframe for its implementation, duration of the NRW-reduction measure, organizational complexity for its implementation and also qualitative assessment of cost efficiency (Fig. 10). DSS also provides the possibility to prioritize operational measures according to six different qualitative criteria, enabling easier classification of the operational NRW-reduction measures and thereby functioning also as an awareness-rising and educational tool.

The level of operational measures and their applicability was recognized as very locally specific and as such it would be very difficult to implement any general decision support procedure.

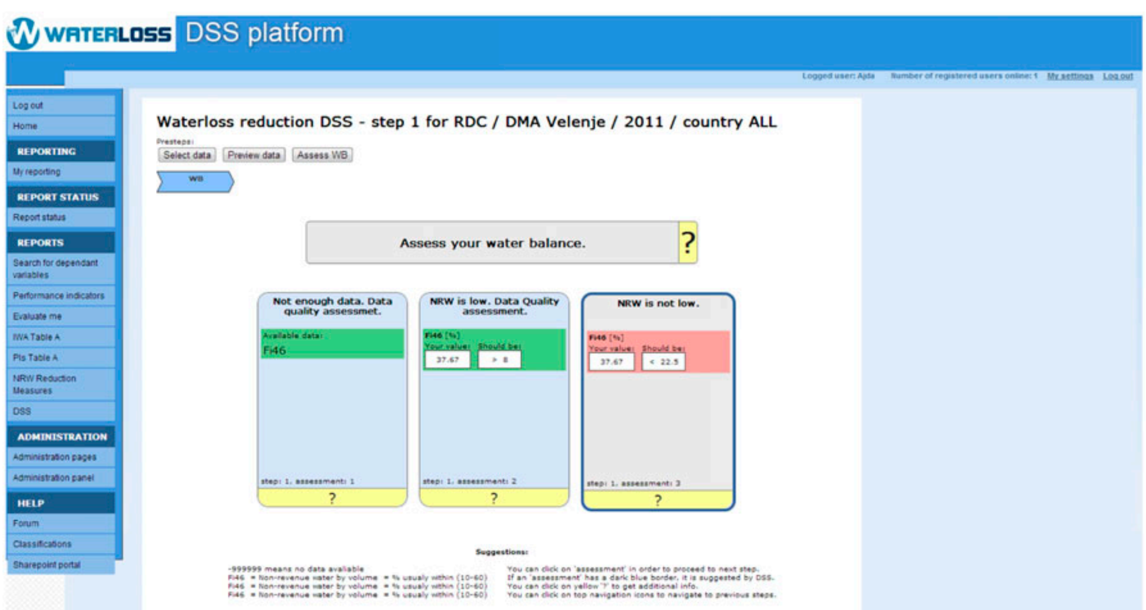

Fig. 8. First step of the supported decision-making process—assessment of the total water balance marked result “NRW is not low”, suggesting the selection of measures in this direction.

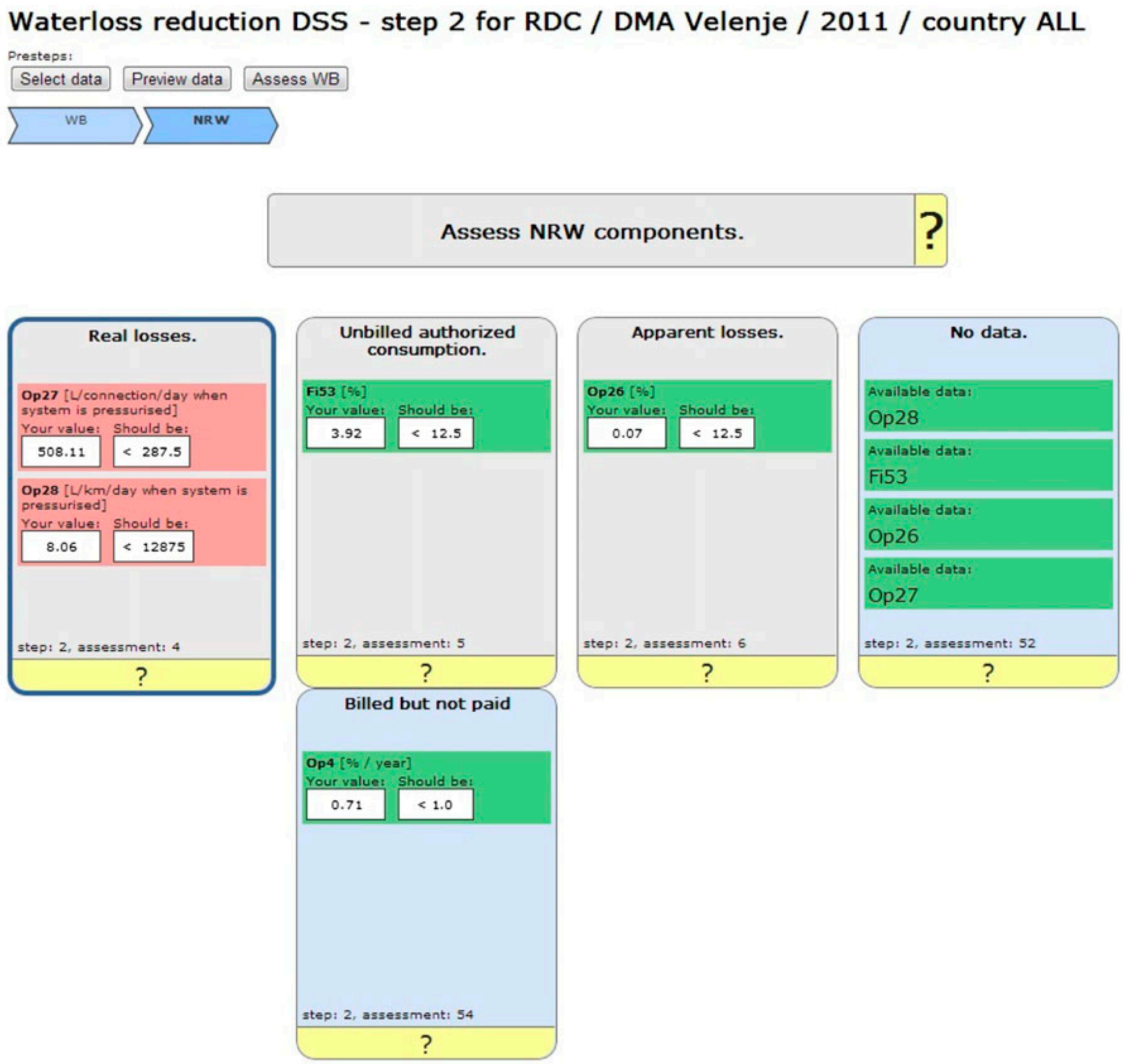

Fig. 9. Second level of the DSS assessing the components of the NRW—real losses are recognized as a priority.

The experience in using the WATERLOSS DSS could be summarized as follows [35]:

(1) The WATERLOSS DSS proved that, even for water utilities that consider they have much information on their WSS, *provision of all the necessary data and information on* WSS and its operation is not a straightforward process. The DSS also has many decision nodes indicating that a user has to collect more data.
(2) In case of high water losses (many participating utilities), many water utilities were clearly directed towards active leakage control measures and WSS-rehabilitation measures. Many WSS are actually performing these measures as part of their NRW-reduction campaigns.
(3) Many water utilities (users) were impressed on learning how many measures lead towards NRW reduction, especially other categories of the water balance apart from real losses. These categories and the NRW-reduction measures are gaining in importance in reducing real losses.
(4) The water utilities realized that there is little awareness on the effects of the NRW-reduction measures applied.

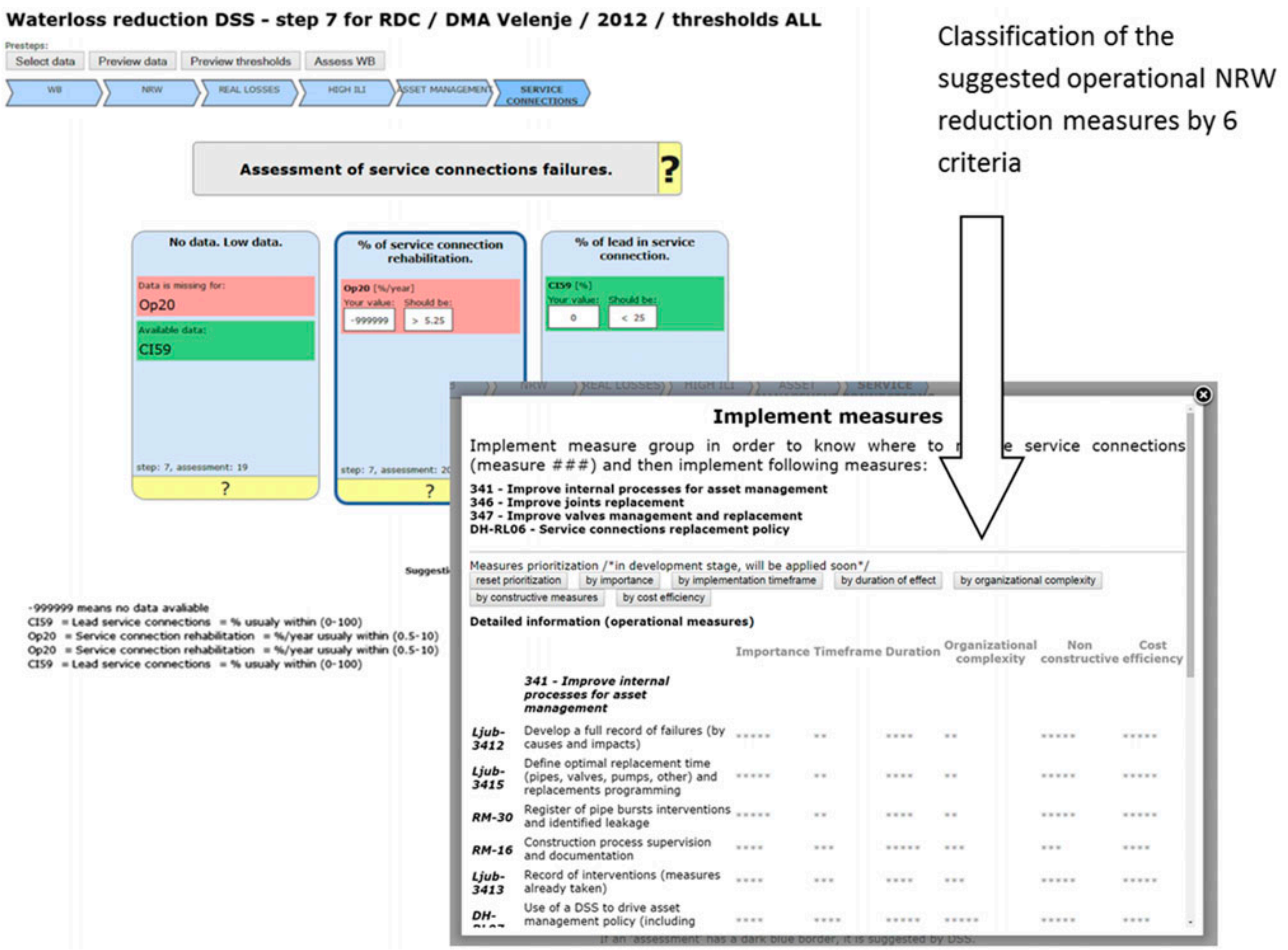

Fig. 10. The last node of the decision support process for the specific WSS (Velenje) with indicated operational measures that could be assigned to this node.

5. Conclusions and future work

The paper explains the approach set by the authors in order to facilitate the decision-making process in the WATERLOSS project. Development of the DSS resulted in some limitations which are described in the paper and which were resolved using the tools and approaches applied for the purpose of the WATERLOSS project. On the other hand, these limitations open a broader discussion on the necessity of developing specific tools in the field of water supply, where especially the need for systematically managed classification of NRW-reduction measures is underlined and the necessity for a collection system for the registry of actual NRW-reduction experiences.

These modules were developed within the WATERLOSS project for the purposes of the project, but the necessity for broader standardization and maintenance of both components in the framework of international scientific and professional community still remains.

The use of the DSS was tested by the water-utility managers and led to several important results. It is important because:

- It is a decision-making tool based on the available information for a specific WSS—the selection of measures is, therefore, not limited to narrow a community of professionals understanding the complexity of WSS and mechanisms of NRW occurrence, but becomes broadly understood and more standardized.
- It identifies the need for a more standardized collection of required data (many key data for the DSS on WSS operation are not readily available for all WSS under consideration). DSS clearly recognizes this missing data and suggests the utility managers that it need to be collected and evaluated.

- It is a tool for identifying the measures for NRW reduction (strategic level and operational level), which allows users (i.e. users who are not WSS managers) to analyse the water supply sector and the domain of NRW-reduction measures for study and educational purposes.
- It provides a platform for the exchange of experience in the actual application of NRW-reduction measures, building a reference set of qualitative descriptors for the future probabilistic node in the next generation of NRW-reduction DSS.

Because of the above-mentioned reasons, the pivotal element of the WATERLOSS project has provided its function with its multipurpose and multiperspective approach providing information and support in the decision-making process for the WATERLOSS partners, and beyond for the all interested target public addressed by specific training seminars and beyond after the conclusion of the project.

The developed DSS also functions as a standard benchmarking tool. Variables are uploaded in the DSS. Using the reporting module, it could be calculated into IWA benchmarking indicators and those could be compared within the pool of users of the DSS. Within the pool of the WATERLOSS project, this number is rather limited and the benchmarking feature has no actual significance.

An important feature that was developed and integrated in the WATERLOSS DSS is described as the first attempt to develop a well-defined classification of NRW-reduction measures. This classification was important for the development of the DSS itself, because the DSS could not be operational without it. It is also important for communication among the project partners, because it has enabled their unique and discernible identification providing in this way a common language among a range of stakeholders involved in the project.

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