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ORIGINAL ARTICLE

Translating the 'water scarcity – water reuse' situation into an information system for decision-making

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Abstract

One key challenge of water resources management is the identification and processing of the information necessary for decision-making. This article aims to provide avenues for translating a 'water scarcity–water reuse' (WS–WR) situation into an information system. It is dedicated to supporting an integrated assessment in decision-making with the final goal of optimising water scarcity risk reduction and water reuse sustainability. The approach combines the following two strands: (1) specific interpretation of systems thinking and (2) systemic characterisation and interlinkage of indicators. The result is an analytical concept that translates the WS–WR situation into an information system consisting of two structured components, a multi-layer (ML) and a lane-based (LB) approach. While the multi-layer approach supports the description of the elements of the biophysical and information systems such as endpoints and descriptors, respectively, the lane-based approach aids in understanding the importance of indicators within the entire system and their distribution across risk and sustainability realms. The findings from a generic exemplification of the analytical concept depict the feasibility of identifying system-based endpoints representing the WS–WR situation and their translation via descriptors to an interlinked indicator set to jointly assess water scarcity risk and sustainability of the water reuse measures. Therefore, this analytical concept supports addressing the water resources management information challenge via a structured representation of the system's complexity and the quantification and visualisation of interlinkages between the social, economic, and environmental dimensions of water scarcity risk and water reuse sustainability.

Keywords Water scarcity · Water reuse · Decision-making · Systems thinking · Indicator interlinkage · Sustainability assessment

Introduction

A challenging situation that decision-makers around the world face is to provide sufficient water in water-scarce areas. One solution is water reuse, i.e., the use of treated wastewater to supply water demands (FAO 2017; Voulvoulis 2018). Decision-makers here are tackling the issue of reducing the risk from decreasing or chronically lacking water quantities to meet human demand while providing sustainable solutions. The authors showed that an integrative way of thinking enables an inclusive decision in this context rather than sticking with the following two separated decisions: one on the reduction of risk and one on sustainable solutions (Müller et al. 2020). Accordingly, an integrated risk and sustainability assessment (RSA) framework has been proposed to analyse and evaluate data and information relevant from both spheres of knowledge resulting in one consolidated decision (ibid.). While this framework conceptually proves

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the possibility of integrating information from these two realms in a comprehensive manner, it still faces the issue of translating data into appropriate information. The latter particularly means how to choose the ‘right’ indicators for the assessment and hence the decision-making.

To carry out comprehensive risk and sustainability assessments for water resources management requires understanding complex interrelations between humans and the natural environment (Simonović 2009). Research in the fields of environmental and natural resources management (e.g., Speelman et al. 2007; Seiffert and Loch 2005) and specifically in water resources management (e.g., Simonović 2009; Davies and Simonovic 2011; Kotir et al. 2016), including risk- and sustainability-related studies, has highlighted the value of systems thinking in addressing complexity (e.g., Seiffert and Loch 2005; Di Baldassarre et al. 2013; Onat et al. 2017; Mai et al. 2020; Rubio-Martin et al. 2020). These approaches aim at reducing the complicatedness of real-world situations by interpreting them as a system, i.e., a sequence of interconnected elements functioning as a whole (Smithson et al. 2008). They support the representation of the situation and understanding of developments by (a) capturing the complexity and providing a big picture (Speelman et al. 2007; Rhoades et al. 2014), and (b) describing dynamics (Davidson and Venning 2011; Kotir et al. 2016; Mai et al. 2020). However, the interpretation (representation and understanding) as a system is strongly dependent on the involved scientists, experts, and actors, their field of knowledge, and their level and kind of expertise (Zamagni et al. 2013; Dalal-Clayton and Sadler 2014; Ricart 2016). Thus, the same situation may lead to different representations that drive indicator selection, where indicators critical for decision-making may be overlooked.

Therefore, bridging a systems view, ideally derived in an inter- and transdisciplinary setting (Bennich et al. 2020), with traditional risk and sustainability assessments may support a consistent selection of indicators for ‘water scarcity–water reuse’ (WS–WR) situations. Insights on the types of indicators can show representation issues, e.g., of the dimensions of sustainability (e.g., Strezov et al. 2017; Oliveira Neto et al. 2018). Moreover, the analysis of the interlinkages between indicators may help identify which ones are critical to put in extra effort for data collection. The latter is supposed to help decision-makers focusing their resources on collecting representative and critical information about the situation, enabling them to see both the system as a whole and interlinkages that may not have been obvious.

This article aims to provide avenues for translating a WS–WR situation into an information system. It is dedicated to support an integrated RSA to optimise water scarcity risk reduction and water reuse sustainability, as described in Müller et al. (2020). The approach combines two strands: (1) specific means of systems thinking for system analysis and (2) systemic characterisation and interlinkage of indicators for the construction of an information system.

The reader can expect a conceptual and methodical article that presents the derivation of an analytical concept and its exemplification in a generic WS–WR situation. Sect. "RSA framework for a WS–WR situation" briefly introduces the RSA framework as proposed by Müller et al. (2020). Section “Systems thinking in a WS–WR situation" describes the interpretation and translation of the situation via a multilayer approach, while section “Characterisation and interlinkage of indicators” expands the analysis via a lane-based approach. Section “RSA analytical concept and exemplification" derives the overall analytical concept and an exemplification of the two approaches. Sections “Discussion” and “Conclusions” further reflect on the analytical concept and its outlook.

RSA framework for a WS-WR situation

The current work builds on the conceptualisation of the RSA framework for the integrated assessment of water scarcity risk and water reuse sustainability (Müller et al. 2020). Risk of water scarcity is understood as the probability of insufficient water quantity to fulfil human demand, where the hazard refers to a decrease in the quantity of water resources for human use, the exposure to the spatial and temporal interrelation of available resources and human demand, and the vulnerability to the human demand of water resources. Sustainability of water reuse refers, in said publication, to contribute fulfilling people’s water demand, the ability of the environment to provide water and its protection from pollution via contaminant-free and ready-to-use treated wastewater, while ensuring economic feasibility and socially just allocation of resources. The framework with the aforementioned key concepts is used in the current article to guide an overall analytical concept for deriving, characterising, and interlinking indicators.

The systems view of the RSA framework bears on a coupled human and natural system (CHANS). It differentiates between the biophysical system of the human–nature interrelations and the immaterial aspects of the human sub-system. This allows to portray material flows according to four water flow categories (source, use, treatment, and reuse) on the one hand, and the respective stakeholders with their interactions on the other (ibid.). In the current article, these two tiers form the basis for the differentiation between a biophysical system interpreting the water and water-related matter flows (section “Systems thinking in a WS–WR situation”) and its translation in an information system with the characterisation of indicators and their interlinkages (section “Characterisation and interlinkage of indicators”).

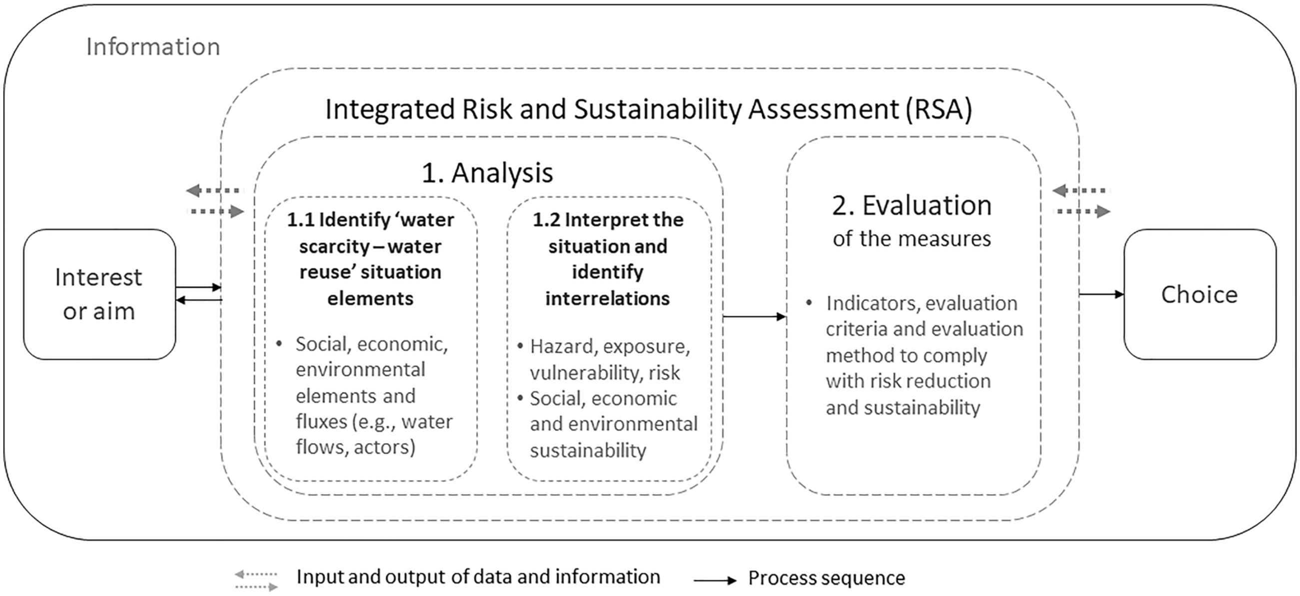

Fig. 1 Integrated RSA framerwork comprising analysis and evaluation (Müller et al. 2020; modified)

The information system supports the decision-making process with its continuous exchange of information. According to typical assessments, the RSA has been structured in a two-task procedure: analysis and evaluation (see Fig. 1). In the analysis, the WS–WR situation is addressed by (1) identifying its relevant elements (step 1.1) and (2) interpreting the situation and interrelations between these elements (step 1.2). The analysis results provide the information necessary for evaluating the water scarcity risk and sustainability of the water reuse measure, bridging the aim and the evaluation within the decision-making process.

So far, the conceptual framework of Müller et al. (2020) could not provide further details on how to derive and organise the information in the analysis to support an appropriate evaluation. Thus, the current article elaborates on an explicit translation from the biophysical (step 1.1) to the information (step 1.2) system.

Systems thinking in a WS–WR situation

On the one hand, systems thinking is generally recognised for addressing complexity (Seiffert and Loch 2005; Nguyen et al. 2015), especially when it comes to the structure, processes and interactions between human and nature for the design, planning and implementation of effective interventions (Alberti et al. 2011; Binder et al. 2013; Rhoades et al. 2014; Lawrence et al. 2020). Whether it is via social-ecological systems -SES- (e.g., Ostrom 2009), coupled human and natural systems -CHANS- (e.g., Liu et al. 2007), or human–environment systems -HES- (e.g., Scholz 2011), to mention a few, these approaches aim at improving the understanding of the situation's complexity. On the other hand, risk and sustainability assessments provide information on the situation to support decision-making. They do not aim to generate just any knowledge about the WS–WR situation but rather targeted knowledge by processing information, in this case, related to risk and sustainability, to evaluate the performance of the situation. Hence, how could the information of a system's interpretation be analysed to support the evaluation?

The following subsections describe which elements of the WS–WR situation should be identified for an interpretation as a biophysical system and its translation into an information system for decision-making.

Identifying elements of a WS–WR situation and its interpretation as a system

System dynamics approaches, e.g., Causal Loop Diagrams (CLD) and Stock-Flow Diagrams (SFD), focus on the interrelation of the system's elements as a means of representing real-world processes and analysing their behaviour over time (Sterman 2000; Winz et al. 2009; Schlüter et al. 2014). Causality interrelations between the elements allow defining balancing and reinforcing loops that characterise this behaviour (Lin et al. 2020). In water resources management, they have been used for identifying key elements (e.g., Simonović 2009; Wu et al. 2020; Yazdandoost et al. 2020) with a focus on biophysical aspects (Kotir et al. 2016).

Thus, the first step in advancing the WS–WR situation's conceptualisation as a CHANS is to identify relevant biophysical elements of water scarcity and water reuse (step 1.1). These elements are named here *endpoints*—to differentiate them from the information system's elements—and represent the state or performance of system processes as system variables. They need to be identified during a system analysis by researchers or expert practitioners and represent all water flow categories (source, use, treatment and reuse). To do so, they can rely on a literature review for a top-down approach or engage in a variety of multi-, inter-, or transdisciplinary activities with different levels of participation for a bottom-up approach (e.g., focus groups, surveys, interviews) (e.g., de Vente et al. 2016; Horlings et al. 2020). Common elements that could be identified as endpoints are also found in SFDs. Endpoints of a system for a WS–WR situation include, e.g., available water resources, supplied water resources, available treated wastewater (more examples are found in section "RSA analytical concept and exemplification" and S2).

Translation of the CHANS into an information system

Descriptors for the translation of the system

Identifying the endpoints allows advancing towards a focused representation of the situation to understand the water-related processes. However, this representation remains at the biophysical level pushing towards the well-recognised challenge of interrelating the social, economic, and environmental aspects (Seiffert and Loch 2005; Simonović 2009) (step 1.2 of the analysis). This challenge seems to be enhanced if the relevant knowledge is widely distributed across disciplines (Sterman 2012; van Vuuren et al. 2016; Onat et al. 2017). Under the frame of an RSA, this mainly entails determining which social, economic and environmental information related to the endpoints should be considered to support decision-making from the perspectives of risk and sustainability. This means translating the biophysical system perspective into an information system with the respective information elements. This information system refers here to a conceptualisation of organised information used by the RSA.

Therefore, the use of *descriptors* is proposed. They are understood as thematic conceptualisations of the meaning of the endpoints, taking (key) system functions or services into account accordingly (e.g., water resources available for human use – see example in section "RSA analytical concept and exemplification" and S2). In other words, descriptors connect the biophysical aspects with the immaterial aspects of the CHANS, in that, endpoints represent the biophysical elements of the CHANS and descriptors the guiding elements of the information system. They should be defined by researchers or expert practitioners depending on the interest and contextual characteristics of the case, aiming at answering, e.g., which information related to the biophysical endpoint is relevant from a social, economic and environmental perspective in terms of risk and sustainability? The answer, and hence the descriptor, needs not yet to be as specific as an indicator to allow for an operationalisation with alternative indicators. As with the endpoints, this relies on top-down or bottom-up approaches such as literature or workshops and surveys, respectively.

Indicators to operationalise the descriptors

Provision of descriptive and partly not directly observable information in a classified manner is commonly made through *indicators* based on one or several *attributes* following specific algorithms (see more about the attributes in section "Characterisation and interlinkage of indicators"). In the case of the RSA, indicators generally employed for monitoring and evaluating the risk of water scarcity and sustainability of water reuse can be used to specify descriptors. Hence, indicators here are understood as information elements that operationalise the descriptors for the respective social, economic, and environmental dimensions. With the use of indicators, it is possible to compare elements that contribute to informing about the level of fulfilment of social, economic, and environmental requirements to reduce the risk and increase the sustainability.

The multi-layer approach: Translation of the CHANS into an information system

Overall, the translation into an information system relies on *endpoints* (CHANS biophysical elements) and *descriptors* and *indicators* (information elements), where one *endpoint* can have one or more *descriptors*, and one *descriptor* one or more *indicators* (see Sect. "RSA analytical concept and exemplification" and S2). The traditional system dynamics visual representations (see Sect. "Identifying elements of a WS–WR situation and its interpretation as a system") do not fully represent this translation. However, multi-layer (ML) diagrams appear helpful as they use layers to portray sequential or hierarchical order, e.g., different scales (e.g., Alcamo 2003; Ewert et al. 2006), or different perspectives of the same basis layer (e.g., Basurko and Mesbahi 2014; Rikalovic and Cocic 2014). These representations have been widely used in social sciences (e.g., Bródka and Kazienko 2018; Di Gregorio et al. 2019), natural sciences (e.g., Rikalovic and Cocic 2014; Vermeulen et al. 2020), and particularly in engineering and computer sciences as "multi-layer networks" (e.g., Kivela et al. 2014; Wu et al. 2019).

Thus, for the RSA analysis task, an ML view helps conceptually capturing the translation into an information system, as shown in Fig. 2. The layers can be understood as the

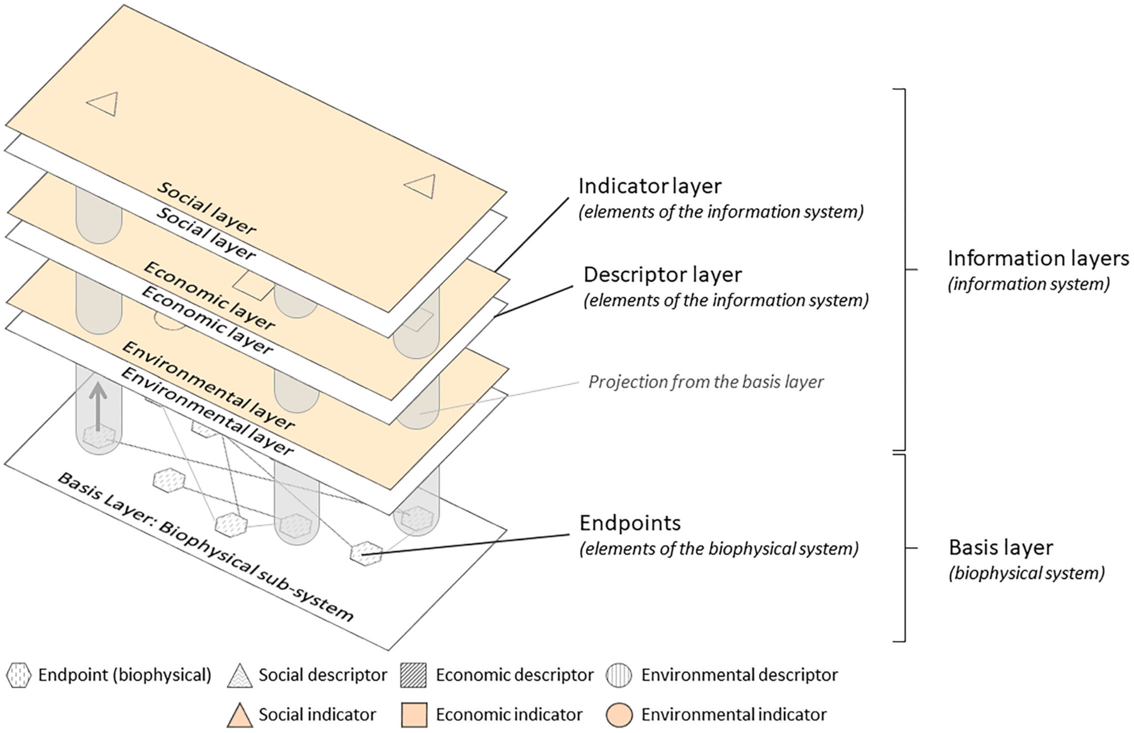

Fig. 2 Representation of the multi-layer (ML) approach

Table 1 Information that can be derived from the information system

	Indicator type			
Dimension	**Risk**	**Risk and sustainability**	**Sustainability**	**Intra-dimensional interlinkages**
Social	So-R indicators	So-RS indicators	So-S indicators	**Social performance**
Economic	Ec-R indicators	Ec-RS indicators	Ec-S indicators	**Economic performance**
Environmental	En-R indicators	En-RS indicators	En-S indicators	**Environmental performance**
Inter-dimensional interlinkages	**Risk-related performance**		**Sustainability-related performance**	**Risk- and sustainability-related social, economic, and environmental performance**

So Social, *Ec* Economic, *En* Environmental, *R* Risk, *S* Sustainability, *RS* Risk and sustainability

interpretation of the biophysical system through the lenses of risk and sustainability and the views of social, economic, and environmental dimensions. This way, the ML approach provides a structure that differentiates the biophysical and the information perspectives while recognising their common origin. Moreover, it mirrors and translates the immaterial perspective by an indicator-based information system.

Table 2 Information about type and number of interlinkages

Information derived from the information system	Relevance for decision-making
(1) Share of intra- and inter-dimensional interlinkages	Indicate whether elements are likely to change due to intra-dimensional aspects, e.g., if social aspects are highly influenced by/influencing other social aspects, or if social, economic, environmental performance is highly interdependent
(2) Share of the types of interlinkages at different levels	Indicate how risk of water scarcity and sustainability of water reuse are correlated
(3) Share of dimension-specific indicator's involvement in intra- and inter-dimensional interlinkages and over the total number of interlinkages in the system	Indicate the role of social, economic, and environmental indicators in the system's performance, as being decisive elements within their specific dimensions or to other dimensions
(4) Share of dimension-specific indicator's involvement in the different types of interlinkages	Indicate the role of specific indicators within the risk perspective, the sustainability perspective, or the correlation between risk and sustainability

This offers an alignment between the analysed WS–WR situation and the information for decision-making.

Characterisation and interlinkage of indicators

So far, relevant information elements (*indicators*) have been identified via the ML translation approach. However, knowledge about the indicators and their interlinkages can support the construction of the information system. For the RSA, identified social, economic, and environmental indicators are characterised as risk-related (R-indicators), sustainability-related (S-indicators), and indicators that are used both in risk and sustainability assessments (RS-indicators), i.e., nine different types of indicators (see Table 1). Depending on the number of indicators identified, their distribution across dimensions may vary.

Interlinkages may exist within each dimension (intra-dimensional) and across them (inter-dimensional). In line with the indicators' characterisation mentioned above, four sorts of interlinkages are possible: (1) between two risk indicators (R–R), (2) between two sustainability indicators (S–S), (3) between risk and sustainability indicators (R–S), and (4) between two RS-indicators (RS–RS). As long as no directionality is specified, R–S is equal to S-R. For the case of interlinkages between RS-indicators with R-indicators or S-indicators, they should be counted as R–R and S–S interlinkages, accordingly.

Based on the different dimensions and types of indicators and interlinkages (see Table 1), it is possible to obtain information about (a) the general social, economic, or environmental performance when looking within each dimension, e.g., the social performance in terms of social risk of water scarcity and sustainability of water reuse (last column); (b) the general water scarcity risk-related or water reuse sustainability-related performance when looking at inter-dimensional- and indicator-type-specific interlinkages, e.g., social, economic, and environmental water scarcity risk-related performance (last row); and (c) about the entire system from both views including all types of indicators and interlinkages (bottom right corner). The latter suggests being the most challenging to process, given all types of indicators and interlinkages. Additionally, the mentioned information can be systematised in terms of (i) type and number of indicators, (ii) type and number of interlinkages, and (iii) indicator's connectivity (ratio of interlinkages per indicator).

Type and number of indicators

Following the ML approach, different types of indicators are identified for the respective descriptors and characterised as mentioned above. The distribution of those indicators across the sustainability dimensions and the water flow categories may vary, allowing the identification of data-intensive areas of the information system, i.e., where more data needs to be collected to provide the required information. On the one hand, variation within each dimension or layer can indicate data-intensive categories. On the other hand, when comparing all the layers, it is possible to analyse contrasting distributions and the most data-intensive dimension. The same can be observed for contrasts between risk- and sustainability-related indicators, e.g., a greater number of R- over S-indicators.

Type and number of interlinkages

Knowing the different types of interlinkages and their share can be a starting point towards deriving a correlation between, e.g., risk of water scarcity and sustainability of water reuse (at least in terms of the data required). Again, this analysis involves counting the number of intra- as well as inter-dimensional interlinkages. As long as there is no causality analysis between the indicators, it is impossible to define the direction of the influences (i.e., influenced or

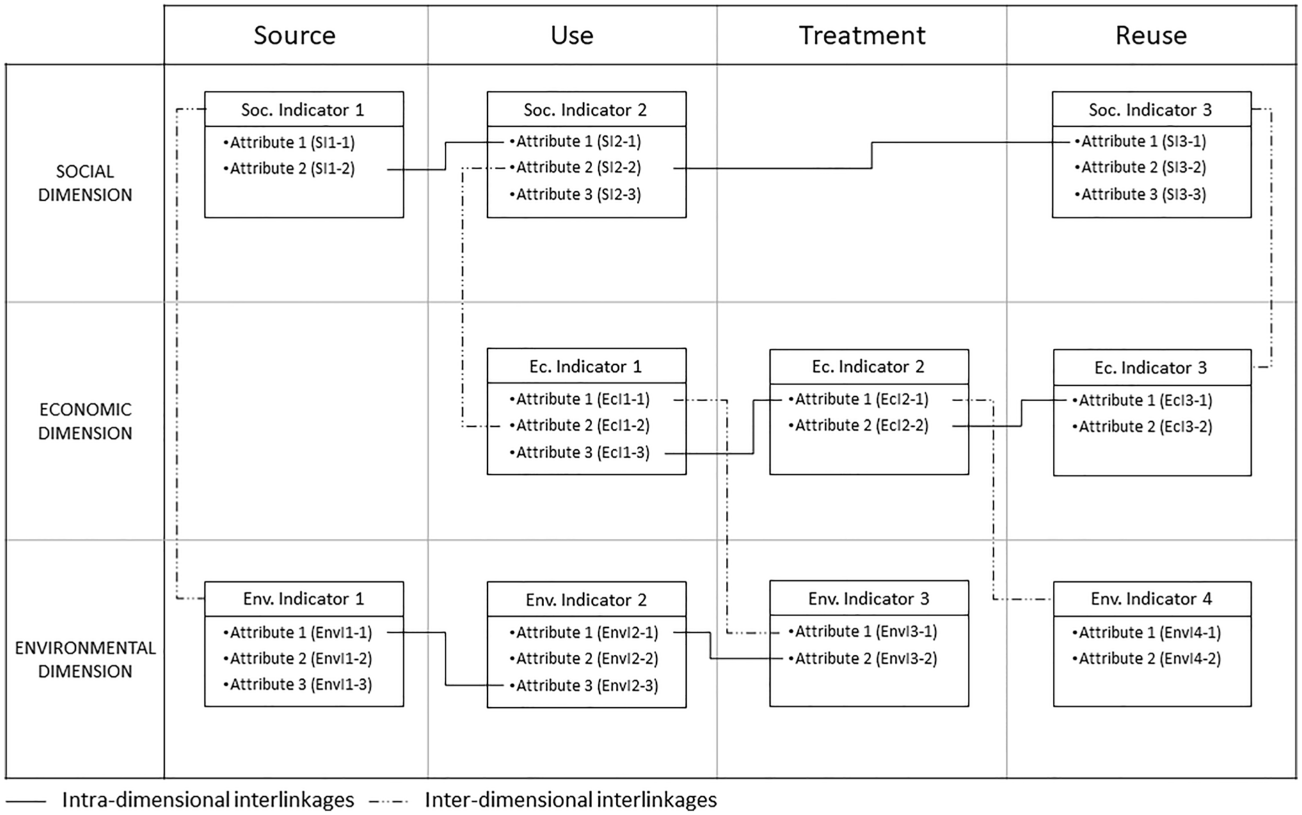

Fig. 3 Lane-based (LB) approach for visualising the WS–WR information system. Schematic representation of an information system comprising three social indicators, three economic indicators, and four environmental indicators. *Indicators* are described by *attributes,* and interlinkages represent the use of the same *attributes* or a direct correlation between two *indicators*

influencing). Table 2 shows, in general, the information that can be drawn from this analysis and its relevance for decision-making. This can be used to define the information system in terms of the interlinkage between the social, economic, and environmental dimensions, as well as between risk and sustainability (as introduced in Table 1).

Indicator connectivity

A rough calculation of the ratio between the number of indicators and the number of interlinkages leads to the indicators' connectivity. Connectivity can be calculated for (i) dimensions, e.g., number of social indicators over the number of interlinkages involving social indicators, (ii) risk and sustainability indicators, and (iii) the dimension-specific risk and sustainability indicators for a more detailed analysis, e.g., to find the most interlinked indicators. This defines the role that a specific type of indicator plays in the performance of the system, for each dimension and also for the risk and sustainability perspectives.

Based on the above, most interlinked indicators (MII) can be identified, i.e., indicators highly influenced by or influencing the system. Thus, if there are changes in the scores[1] of other indicators, it is highly likely that these MII also change; or if the score of an MII changes it is highly likely that the scores of multiple other indicators do too. This supports an optimised evaluation of the system, prioritising getting data for MIIs over others. It also supports identifying leverage points for reducing risk of water scarcity and increasing the sustainability of the water reuse measure. Again, depending on the aim of the study, it is possible to find the MII within each dimension, within the risk and sustainability perspectives, or both. For instance, if the MIIs belong to the social dimension and mainly correspond to sustainability indicators, it calls for focusing on interventions that affect these indicators to increase sustainability. All of this information requests a structured and a compartmentalised approach for its visualisation and analysis.

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[1] Here *score* is understood as the quantitative or qualitative measured value of an indicator, not referring to their relevance for the system.

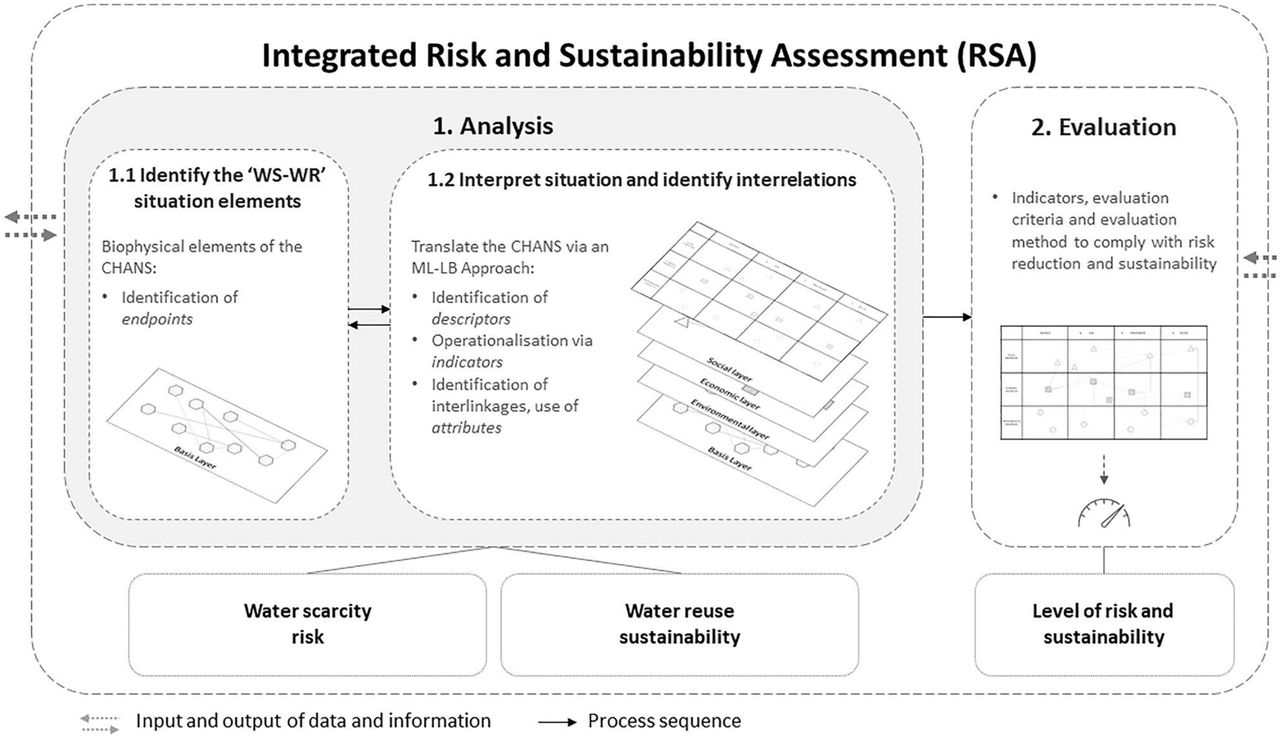

Fig. 4 Analytical concept embedded in the RSA framework. Based on Müller et al. (2020)

Structuring via a lane-based approach

The three-dimensional layout of the ML approach might not be the best way of clearly visualising all the indicators and interlinkages. Here, it appears useful to refer to disciplines in business and industrial processes management, where different departments, functions, and activities have to be coordinated to provide a final product or service. This also means that different "dimensions" have to be portrayed together for a comprehensive view of the processes. A widely used diagram that portrays this is the Business Process Model and Notation (BPMN). While developed around 20 years ago (White 2004), it has been further advanced and ratified as a standard—ISO/IEC 19,510:2013 (ISO 2013; OMG 2013). The main goal is to support the general understandability of processes (White et al. 2004; OMG 2013), where activities are organised within different lanes (OMG 2013). These lanes allow a compartmentalised visualisation of the workflows, i.e., interactions, between "*internal roles (e.g., Manager, Associate), systems (e.g., an enterprise application), an internal department (e.g., shipping, finance)*" (OMG 2013, p. 305). Similarly, the RSA analysis aims at providing decision-makers with an understandable representation of the interactions within the WS–WR situation. Therefore, it seems suitable to use a lane-based (LB) approach to represent the different indicator layers resulting from the ML approach (i.e., the dimensions of sustainability), as shown in Fig. 3.

For the interlinkage analysis, in line with Entity–Relationship Diagrams (ERD) and Unified Modelling Language® (UML®), two standard approaches used to portray information systems (Chen 1976; OMG 2017), systems elements – entities in ERD and classes in UML® – can be further disaggregated into their fundamental components called *attributes*. Connections can be established between the different elements based on the presence of the same attributes or the use of an attribute to derive another. For the WS–WR information system, *indicators* are portrayed in terms of their *attributes*, i.e., the most basic measurements used for calculating their score. Then interlinkages could be identified between *indicators* if two *indicators* have the same *attribute* or if there is a known correlation between them or their *attributes*. Thus, there is a hierarchical order between *endpoints*, *descriptors*, *indicators*, and *attributes*. Endpoints are described by social, economic, and environmental generic *descriptors*, which are operationalised through *indicators* that are further defined by *attributes*. The result is a network map that allows following the consequences of the changes in the scores of the *indicators* for a more detailed analysis of the performance of the system (see Fig. 3). For instance, if the indicator score changes because of one *attribute*, then the score of other *indicators* linked to

Table 3 Literature review search string and results

	Water scarcity risk	Water reuse sustainability
Search string	TITLE ("water scarcity" AND (risk OR vulnerability)) LANGUAGE (English) DOCTYPE (ar) AND EXCLUDE (PUBYEAR, 2020)	TITLE ((“water reuse" OR "wastewater reuse") AND sustainability) LANGUAGE (English) DOCTYPE (ar) AND EXCLUDE (PUBYEAR, 2020)
Search results	26	11

this *attribute* may also change, i.e., variations in one *indicator* might mean variations of other linked *indicators*.

RSA analytical concept and exemplification

RSA analytical concept

Based on the described approaches, the analytical concept proposed here advances the RSA and the interpretation of a WS–WR situation as a CHANS by translating it into an information system via an ML approach involving the identification of relevant *endpoints* (step 1.1) and social, economic and environmental *descriptors* and their respective *indicators* (step 1.2). It also proposes to analyse existing interlinkages by considering *attributes* and structure the visualisation of these interlinkages via an LB approach (step 1.2). Figure 4 shows a schematic view of the RSA containing the analytical concept, including the final LB grid as the starting point for the evaluation. Since the RSA is not prescriptive regarding the evaluation method, further specification exceeds the scope of this publication.

Exemplification of the analytical concept

As mentioned, the interpretation of a situation relies on the involved researchers and experts; thus, existing studies of specific cases, including water scarcity and water reuse, can support a generic but detailed enough exemplification of the analytical concept. An overview of the literature shows a plethora of risk- and sustainability-related indicators used in assessments for water resources management (e.g., Collins and Bolin 2007; Muga and Mihelcic 2008; Juwana et al. 2012; Damkjaer and Taylor 2017). Rather than a general literature review, a systematic search was carried out looking for scientific articles that provide a list of indicators used for the evaluation of risk of water scarcity and sustainability of water reuse. The chosen database was Scopus, considering articles written in English before 2020. Table 3 presents the search strings and the found records (see the complete list in S1). To focus the search and facilitate the filtering process the search terms had to be contained in the title. Articles were then filtered by title and content according to two inclusion criteria as follows: (1) align with the terminology of the RSA (e.g., ‘water scarcity’ instead of ‘water stress’, ‘reuse’ instead of ‘reclamation’ or ‘recycling’), and (2) explicitly mention the indicators used to evaluate risk or sustainability.

As no articles simultaneously assessing risk of water scarcity and sustainability of water reuse were found, three scientific articles were selected. On the one hand, risk components are covered by Collins and Bolin (2007) referring to societal and biophysical indicators to assess vulnerability to water scarcity, and by Veldkamp et al. (2016) referring to the exposure component of this risk. On the other hand, Upadhyaya and Moore (2012) provide a list of indicators to assess the sustainability of rural water reuse. These articles were found to satisfy the selection criteria.

Based on the information provided in the articles, corresponding endpoints and descriptors were derived by the authors as well as interlinkages between indicators. The interlinkages were identified manually using a matrix for pairwise comparison between indicators. Interlinkages were assigned based on the following two criteria: (1) the use of the same attribute (e.g., use of the attribute ‘total number of housing units’ in indicators ‘total housing units’ and ‘mean housing value’), or (2) correlations between the scores of the indicators (e.g., between ‘quantity of wastewater reused’ and ‘energy consumption for reuse component’ or between ‘aesthetics (colour, odour)’ and ‘complaints reported to the authority’).

Defining endpoints and translating them into an information system

The biophysical system proposed by the authors (Müller et al. 2020) was used to specify the endpoints. They mainly refer to water quantity aspects in the water flow categories: source (e.g., available groundwater), use (e.g., water supply and water requirements), treatment (e.g., water in wastewater treatment plant—WWTP) and reuse (e.g., treated wastewater for reuse). These endpoints were also compared with literature on system dynamics approaches for water resources management (e.g., Winz et al. 2009; Yazdandoost et al. 2020).

Descriptors were defined for the endpoints and thematically specified based on the RSA information demand as visible from the indicators gained through the literature review (see following sub-section). Table 4 shows selected examples of endpoints in the different water flow categories and

Table 4 Selected example endpoints, descriptors, indicators and attributes for a generic WS–WR situation and the RSA framework

Category	Endpoint	Dimension	Descriptor	Indicator	Attribute	Type
SOURCE	Available groundwater	Environ-mental	Water resources available for human use	Water crowding index	Daily runoff Water province area Time slice (e.g., 30 y) Return period Climate change projection Total population	R
USE	Water resources supplied	Social	Drinking water supply	Proportion of housing units within municipal water provider service area	Housing units within municipal water Total population	R
TREATMENT	Wastewater treatment operation and maintenance	Economic	Economic feasibility	Benefit–cost ratio	Benefits quantification	S
				Ongoing benefits	Costs quantification Benefits to broader community	S
					Operational costs	S
REUSE	Treated wastewater for human reuse	Environ-mental	Treated wastewater for reuse in agriculture	Quantity of wastewater reused	Quantity of wastewater reused Total treated wastewater	S

R Risk-indicator, *S* Sustainability-indicator. See the complete example list in S2

their respective descriptors, indicators and attributes (see the complete list in S2). For instance, in the treatment category, the endpoint related to operational aspects of the WWTP can be described by health and security issues, operational and maintenance costs, and operation standards from a social, economic, and environmental perspective, respectively. Furthermore, a descriptor can be operationalised by more than one indicator, e.g., economic feasibility related to the wastewater treatment is defined in terms of the benefit–cost ratio, as well as the ongoing overall benefits.

Characterising the indicators and analysing their interlinkages

For the LB analysis, a total of 41 indicators[2] were identified and characterised, assigning them accordingly to the specific water flow categories, as shown in Fig. 3 (see Fig. 5 and the complete list in S2). The analysis involved looking at the type and number of indicators within and across dimensions, and the characterisation of interlinkages according to Table 1. Table 5 presents the number of indicators and interlinkages behind the required information, and the following sub-sections describe this information.

Type and number of indicators

Results show an information system characterised by a higher number of environmental indicators, accounting for almost 50% (see Fig. 5). The social dimension shows a balanced distribution of the R- and S-indicators, contrasting with the economic and environmental dimensions with a prevalence of S- over R-indicators. From a risk perspective, the main share belongs to social indicators (around 60%) with a somewhat balanced distribution of economic and environmental indicators. From a sustainability perspective, there is an almost direct swap in proportions between social and environmental indicators, as 60% of the S-indicators refer to environmental aspects. Thus, in this case, social information seems highly relevant from a risk perspective, whereas assessing sustainability relies heavily on environmental aspects.

No overlapping indicators (RS) were found, and R-indicators characterise only one-third of the entire system attributing the main contribution to S-indicators. This suggests that the data required for the risk and sustainability assessments are different and that sustainability-related aspects majorly define the system's performance.

Regarding the indicators' distribution, environmental indicators are relevant for the source and reuse category of the water flow. In contrast, the use category does not include this type of indicators. Social indicators seem relevant for characterising the use and reuse categories, and economic indicators are distributed evenly from the use to the reuse categories.

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[2] Two vulnerability indicators referring to race and ethnicity (Collins and Bolin, 2007) were not included as they were considered to be case-specific for the example addressed in that study. Two economic sustainability indicators (Upadhyaya and Moore, 2012) were repeated for the 'Treatment' and 'Reuse' categories, as they are separated in the RSA framework.

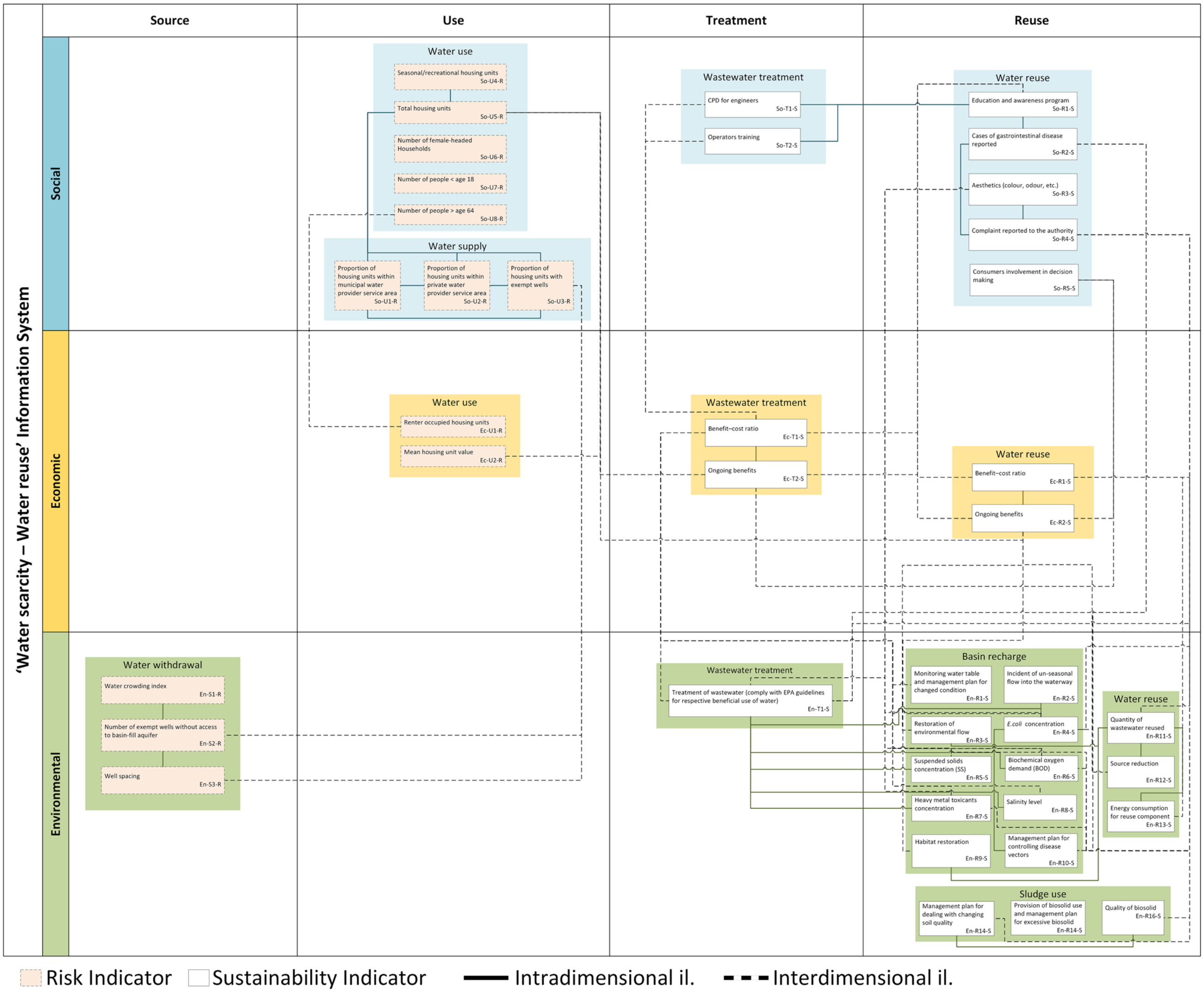

Fig. 5 Overview of the lane-based visualisation of all layers, the indicators and interlinkages (il.). Attributes are omitted for want of space (The details are provided in the online figure; the full list of indicators is accessible under S2)

Type and number of interlinkages

From an intra-dimensional perspective, 28 interlinkages (il.) were identified, with a major share of S–S interlinkages (67.8%). However, this share aligns with the number of S-indicators (68.3%), which hampers inferring, at this point, that the S-indicators are more interconnected than R-indicators (see following sub-section). It is possible, though, to see that changes in risk indicators seem more relevant from a social perspective. In contrast, the dynamics from a sustainability perspective seem particularly relevant for the environmental dimension.

From an inter-dimensional perspective, 43 il. were identified involving high participation of social and environmental indicators (both involved in 72.1%), whereas economic indicators participate in 55.8% of the interlinkages. All inter-dimensional R-related interlinkages involve social indicators, although they represent only 9% of the inter-dimensional view. Thus, in this example, the R-indicators do not highly influence system dynamics but are highly dependent on social aspects. In contrast, most of the interlinkages involve S-indicators; thus, the inter-dimensional influence becomes more relevant for water reuse than for water scarcity.

Overall, the share between intra- and inter-dimensional interlinkages (around 39.4% and 60.6%, respectively) shows that dimensions are highly interconnected. This interconnectivity majorly characterises the system, where both social and environmental aspects are highly influenced or influencing. Concerning a potential correlation between the

Table 5 Data of the example system: Number of indicators and interlinkages (il.) according to Table 1

		Indicator Type				Intra-dimensional il.			
	Dimension	**R**	**RS**	**S**	**Total**	**R-R**	**R-S**	**S-S**	**Total**
	Social	8	0	7	15	7	0	5	12
	Economic	2	0	4	6	0	0	2	2
	Environmental	3	0	17	20	2	0	12	14
	Total	13	0	28	**41**	9	0	19	**28**
Inter-dimensional il.	**Social**	4	2	25	31	11	2	30	43
	Economic	2	2	20	24	2	2	22	26
	Environmental	2	0	29	31	4	0	41	45
	Total*	4	2	37	**43**	13	2	56	**71**
		R-R	**R-S**	**S-S**					

R Risk, *S* Sustainability

*Sum of all interlinkages for eachindicator type divided by two to avoid double counting as one interlinkage involves two indicators

type and number of indicators and the interlinkages, even when a similar trend was found at an intra-dimensional level (similar ratio between R- and S-indicators, and R- and S-related interlinkages), this was not maintained on a general level, as the S-related interlinkages greatly prevail over R-related ones. The latter account for 18.3% of all interlinkages, indicating a minor influence of this type of indicators on the information system. In contrast, the number of interlinkages characterises the information system as being highly dependent on sustainability indicators (particularly social and environmental aspects), as they are involved in the majority of intra- and inter-dimensional interlinkages. Regarding a correlation between risk and sustainability, counting with no RS-indicators and an almost negligible number of R-S interlinkages allows inferring that, under the current representation, no considerable changes in the level of risk are expected by changing levels of sustainability, or vice versa.

Indicator connectivity

A general overview of the average indicator's connectivity in each dimension shows a higher value for environmental indicators (0.44 il. per indicator), followed by the social and economic indicators (0.35 and 0.23 il. per indicator, respectively). However, the top three MII include one indicator of each dimension as follows: "Complaint reported to the authority" (social S-indicator, 11 il.), "Benefit–cost ratio" (economic S-indicator, 11 il.) and "Treatment of wastewater (compliance with guidelines)" (environmental S-indicator, 10 il.). This means that even though economic aspects do not appear as relevant according in general terms, one of their indicators has the highest specific connectivity. Hence, the relevance of this analysis.

Overall results

The ML-LB approach can support decision-making, as it provides the following overarching insights from the example WS–WR information system: (a) leverage points for an overall improvement of the risk and sustainability performance of the W–WR situation are likely to be linked to the sustainability of water reuse rather than the risk of water scarcity; (b) interventions could target social and environmental sustainability-related aspects as they are highly interlinked in the information system; (c) primary interventions related to social aspects are to be planned for the use and treatment categories; and (d) environmental interventions should focus on the source and treatment of water resources. Further interpretations could be drawn if more specific questions are placed, reaching even a level of specific performance of indicators, e.g., how influential is the indicator "Quantity of wastewater reused" for social sustainability aspect?

Discussion

Translating the CHANS into an information system

The identification of CHANS biophysical elements and a direct and organised translation into an information system seems adequate as this needs to be done anyway for assessments. All assessment tasks, from problem framing to selecting evaluation indicators and criteria, occur on an information level. However, the "small" step of interpreting a real-world situation to be analysed and evaluated involves various minor decisions regarding the aspects to include, increasing the subjectivity of the assessment — for instance, the ongoing debate about the appropriate selection of indicators. De Olde et al. (2017) highlight the relevance of transparency and collaboration in the selection process for the success of the assessment. If no proper attention is given to this process, there is a risk of an inadequate assessment where information is derived from indicators that do not necessarily represent the situation or align with the initial aim (e.g., Zijp et al. 2017) . Hence it is relevant to move towards a transparent and systematic approach for identifying the relevant biophysical aspects (*endpoints*) and required information (*descriptors*) with the respective metrics (*indicators* and *attributes*).

The United Nations Department of Economic and Social Affairs (UNDESA) has recognised the relevance of indicators for policy-making by valuing their incorporation of knowledge from natural and social sciences into decision-making (United Nations 2007). Thus, they are widely used and accepted metrics that allow gathering scattered, siloed and discipline-specific information (Walmsley 2002; Ciegis et al. 2009). Their use as operationalisation elements seems appropriate as they allow remaining connected to different disciplines while including them as part of a broader interdisciplinary assessment, enabling incorporating different knowledge. Zijp et al. (2017) review different methods used in sustainability assessments highlighting that the link between the used metrics and the "*question at hand*" (the aim) could be further improved. Thus, the inclusion of indicators in the analysis phase as elements derived from the translation of the biophysical endpoints should support such an alignment.

When interpreting the results of this analytical concept, it should be considered that indicators are mere operational metrics that do not fully represent the complexity of the situation, where more profound social, economic, and environmental management issues might be overlooked. Their intention is to represent specific parts of the system that are of interest to be evaluated, offering a pragmatic view. This limitation, existing in any indicator-based assessment, is now explicitly evidenced by showing the proportion of the type of indicators and their interlinkages, leading to questions such as: Are environmental aspects underrepresented for the evaluation of risk of water scarcity? What is the relevance of having differences in the number of indicators between the different types? These questions can then be specifically addressed on case-by-case basis to improve existing indicators or derive new ones and refine the interpretation of the evaluation results (i.e., high or low risk and sustainability performance). Ultimately, more profound issues, even related to governance, political and participation aspects could be measured through indicators (e.g., Upadhyaya and Moore, 2012; OECD 2018), but this would mean an increase in the number of indicators considered for the analysis, aligning with the plethora of indicators found in literature and intensifying the data requirements.

From a systems perspective, endpoints are not different from the elements in CLD or SFD. However, they are named here to differentiate them from the elements composing the information system. Other systems' analysis approaches such as the SES analysis framework (Ostrom, 2009) or system dynamics, have the aim of studying the functioning of a system to understand a real-world situation. Thus, they may support the identification of endpoints and descriptors. However, they do not necessarily narrow down the focus to understand the functioning from a performance point of view. Here indicators are required together with defined thresholds to achieve the desired performance, which can also represent the subjective aims of the involved stakeholders. Thus, there are two strands: on the one hand, assessments supporting decision-making can sometimes be distant or misrepresenting the situation (e.g., focused mainly on environmental aspects). On the other hand, complex systems modelling are challenging to operationalise and present to practitioners. This way, the analytical concept proposed here does not intend to replace other systems thinking approaches but bridge a systems conceptualisation with traditional indicator-based assessments, compromising some level of detail on both sides and providing complementary information.

Supporting decision-making via the analytical concept

Based on the above, the analytical concept derived in this study provides a structured and systematic manner for a transparent transition from the conceptualisation of a WS–WR situation as a system to its assessment based on indicators, bridging the real-world subject of the assessment with the information needs.

The ML–LB approach helps to grasp the idea of translating the biophysical elements of the CHANS into an information system. It allows a general vision of the information system while keeping a view of the different dimensions.

As mentioned in Sect. "The multi-layer approach: Translation of the CHANS into an information system", this type of approach has been widely used, succeeding in presenting complex interlinked systems as networks. Furthermore, the evidence-based identification of interlinkages between *indicators* advances towards an integrated characterisation of the WS-WR situation. It allows determining key indicators and data-intensive aspects, supporting, e.g., data prioritisation, indicator selection. This has also been recognised as relevant in other fields dealing with complex systems, e.g., resource nexus (e.g., Laspidou et al. 2020). However, interlinkage directionality, based on features such as causality, was not considered. Examples of this are the identification of balancing and reinforcing loops on CLDs, or the "If–Then" approach considered by Rubio-Martin et al. (2020) for drought management. These causality-driven approaches allow a more accurate representation and understanding of the system's dynamics. For instance, if indicators A and B are interlinked in a direction of A influencing B, the change in A leads to a specific change in B, rather than the other way around. In the current status of the analytical concept, A and B are not defined in terms of which is the influencing and influenced indicator. Thus, predicting future changes will only be as accurate as recognising that a change in A might mean a change in B and vice versa.

Additionally, spatial–temporal features were not further detailed in this analytical concept beyond their indirect inclusion via indicators. These features should be minded for the interpretation of the ML–LB results. For instance, annually based indicators such as "Mean annual precipitation" or "Annual water resources extraction" could be considered as relevant as "Net present value", which depends on the project's evaluation horizon for its calculation. This is also an aspect highlighted by Nilsson et al. (2018) for the case of interactions between the SDGs.

Regarding the visual aspects of the analytical concept, conceptual maps are a means of explicitly portraying complexity, as it probably exceeds the capacity to conceptualise it in mental models (Nguyen et al. 2015), and especially to analyse existing interlinkages between the system's elements (e.g., Davies and Simonovic 2011; Mirchi et al. 2012; Sterman 2012; Di Baldassarre et al. 2013). They have been recognised as essential modelling tools that support the understanding of the system, model design, identifying leverage points and communication with stakeholders (Rhoades et al. 2014; Voinov 2018). Here the ML–LB approach can serve as a basis for more sophisticated visualisations of the information system showing all dimensions simultaneously. It allows presenting these dimensions separately, keeping their specific focus unaltered, while visualising the interlinkages between them in a compartmentalised manner providing the *big picture*. However, this relevant visualisation tool needs to be accompanied by a table summarising all the information, awarding flexibility about its content and detail level depending on the aim and audience (e.g., focus on inter-dimensional aspects). The wide use of BPMN in the business sector corroborates the use of lanes for organising, in this case, indicators from different dimensions, in a structured and straightforward manner. Explicitly portraying relationships within the system raises the usefulness of such notation for systems thinking, stressing its relevance for structured and transparent communication of the model (Hinkel et al. 2014; Schlüter et al. 2014). This is relevant for decision-making and inter- and transdisciplinary research in general (Liu et al. 2007; Voinov 2018), as well as building and maintaining trust among stakeholders and the general public in water resources management (Hartley 2006).

Overall, the analytical concept proposed here can support the implementation of international agreements and guidelines such as the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (SDGs). Within the Sendai Framework, it aligns with the priorities for action related to the understanding of risk (primarily the use of baselines and the analysis of information) and the goal of implementing risk reduction measures considering social, economic and environmental aspects, contributing to the target of increasing the availability of information and assessments. Within the SDGs, this concept relates to goals 6 and 11 by supporting the implementation of water reuse measures and aiming at reducing people affected by water scarcity and by aligning with the Sendai Framework, respectively.

Conclusions

Within the frame of an integrated RSA for WS–WR situations, analysis and evaluation tasks should organise and process relevant information for decision-making (Müller et al. 2020). Intending to further advance the analysis task, this article brings together perspectives from different disciplines for translating these situations into information systems based on systems thinking interpretation and characterisation and interlinkage of indicators. This results in the derivation of an analytical concept comprising the following: (1) the identification of relevant *endpoints* in the biophysical system, (2) the use of a multi-layer (ML) approach for the translation into an information system based on *descriptors* and *indicators* and (3) the use of a lane-based (LB) approach for clear visualisation and analysis of these layers and the respective interlinkages.

The analytical concept bears on interpreting the WS–WR situations as a CHANS and translating it into an information system to comply with the requirements of minimising the risk of water scarcity and maximising the sustainability of water reuse rather than providing a general understanding of the CHANS dynamics. The ML–LB approach uses the sustainability dimensions to develop, process and portray relevant information to guide the RSA for comprehensive and consistent support of decision-making in WS–WR situations. Therefore, it is key to include *indicators*, typically used in evaluations, already in the analysis. The identification of interlinkages between these *indicators* at both intra- and inter-dimensional levels enables extracting information about the social, economic and environmental perspectives separately or as a whole, as well as identifying the risk- and sustainability-related performances. These results are defined in terms of the type and number of indicators and interlinkages, and the indicator's connectivity. Finally, the information system's visualisation in a compartmentalised manner differentiates the *foci* of each dimension while providing the *big picture*.

This analytical concept allows moving the attention from fully understanding the situation to dealing with the information relevant for its management. The ultimate goal of this is to offer the possibility of optimising data collection by, e.g., prioritising highly interlinked indicators and support the identification of leverage points for the design of interventions. Thus, the added value of an ML–LB analysis is three-fold as follows: (1) acknowledgement and systematisation of the translation from the real-world situation to an information system for the identification of valuable indicators; (2) the delivery of evidence-based information in a structured manner, allowing to explicitly quantify the interlinkages across social, economic and environmental dimensions; and (3) the application of a map to visualise these interlinkages and support clear communication and knowledge transfer with decision-makers and stakeholders.

Current limitations and improvement points of the proposed analytical concept include (a) a systematic approach to guide the research team in defining relevant *endpoints* and *descriptors*, (b) interlinkage directionality, (c) lack of a database of indicators and their respective attributes that facilitates interlinkage identification and (d) inherent limitations of indicator-based approaches not fully representing the complexity of the situation. A tool that supports automation could also facilitate the process (e.g., generation of the layers and lanes, counting interlinkages, generating database). This seems an achievable outlook, as data processing here does not involve complicated calculations, and the existing variety of visualisation and data analysis software that could serve as inspiration is broad and widely used (e.g., Tableau®, Qlik®, Power BI®).

A general outlook of this work is the potential use of the analytical concept beyond water scarcity risk and water reuse sustainability, as its structure is not limited to these types of *descriptors* and *indicators*. Subsequent research could focus on studying the implications of interlinkage directionality and developing a database and software tools that support automation.

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