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A relational social-ecological systems approach to determine essential variables for monitoring sustainability at a catchment level

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ABSTRACT

This publication introduces Essential Social-Ecological System Variables (ESEVs), an approach aimed at addressing integration and monitoring challenges in Social-Ecological System (SES) projects at the catchment scale. ESEVs are defined as 'the minimum set of critical social-ecological variables to capture key features, processes, and interactions driving SES dynamics over time and space.' Notably, ESEVs differ from other essential variable approaches as they are based on the relational connection between the 'Social' and 'Ecological' aspects of SESs and are derived from a transdisciplinary process involving systems thinking and social learning. The ESESV approach was rooted in systems thinking to identify variables for monitoring progress towards improved SES sustainability within the Tsitsa River Catchment in South Africa. ESEVs were identified through a process involving interviews, workshops, and surveys with experts from a transdisciplinary SES project in the catchment. The criteria for prioritizing ESEVs and their associated indicators were determined based on 'essentiality scores,' and the degree of consensus among participants. The resulting ESEVs for the Tsitsa River Catchment included 'soil erosion related to human actions on the land,' 'participation in natural resource governance,' 'grazing and rangeland sustainability,' and 'land cover and condition.' Additionally, participants proposed 'access to water,' 'local natural resource governance system,' and 'human well-being in the landscape' as potential ESEVs. Monitoring ESEVs could be achieved through a mix of data sources, with reduced emphasis on biophysical earth observations. Applying the ESEV approach at the catchment scale ensured its contextual relevance and practicality. The study provides valuable insights for monitoring SES sustainability, offering an effective approach and process applicable to various SES landscapes.

1. Introduction

Social-ecological systems (SESs) are integrated systems where strong connections and feedbacks within and between social and ecological elements determine overall system dynamics (Biggs et al., 2021; Folke et al., 2010). As such, SESs are characterized as

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complex adaptive systems, which exhibit system behavior driven by dynamic relational and contextual processes (Preiser et al., 2018).

Integrated monitoring of complex SESs remains a research area in need of further development (Gurney et al., 2019; Itzkin et al., 2022; Schlüter et al., 2021). Effective SES monitoring requires innovative methods and frameworks that account for the unique features of complex SESs (Rosenberg and Kotschy, 2020). However, practical applications of integrated social-ecological monitoring of SESs in real-world scenarios remain limited (Gurney et al., 2019; Selomane et al., 2019), hindered by conceptual disparities, terminological variations, and disciplinary compartmentalization. Furthermore, the inherent complexity and involvement of multiple disciplines in SESs predispose monitoring to 'data overload' issues, which is a common challenge in many monitoring programmes (Lehmann et al., 2020a).

This study proposes a new integrated social-ecological monitoring approach, the essential social-ecological system variable (ESEV) approach. The ESEV approach can address SES integration and monitoring challenges, including data overload and the need for participatory approaches (Itzkin et al., 2022). Since ESEVs would be context-specific, the research adopts a transdisciplinary approach, incorporating participatory methods such as interviews, workshops, and surveys with experts from various disciplines to develop ESEVs for a single case-study, the Tsitsa River Catchment, in South Africa. The overall objectives of this research are thus to propose a concept (ESEVs) and a method (participatory approaches) to develop them within the context of a complex SES case study. This collaborative process resulted in the identification of four ESEVs, considered essential for integrated SES monitoring of this specific catchment.

1.1. Essential Variable concept and applications

In this paper Essential Variables (EVs) were explored as a monitoring approach for SES projects at a catchment scale. EVs have been defined as the minimum set of critical variables needed to capture the key dimensions of a system of interest in the most efficient and cost-effective way possible (Reyers et al., 2017). EVs should be represented by indicators (Proença et al., 2017). For each EV more than one related indicator is adopted (Wu et al., 2021). Early applications of the EV concept include Essential Climate Variables (Bojinski et al., 2014), Essential Ocean Variables (Constable et al., 2016) and Essential Biodiversity Variables (Pereira et al., 2013). Earth Observation (EO) played a big role in earlier EVs, which had a biophysical focus. Biologically relevant variables have been documented in many EV frameworks, but social variables have been lacking and more difficult to incorporate (Reyers et al., 2017; Wu et al., 2021).

However, there has been a recent shift recognizing the need for more integrated EVs. This shift towards a more integrated SES approach can be seen in literature proposing EVs for the Sustainable Development Goals (Fukui et al., 2021; Kussul et al., 2020; Plag and Jules-Plag, 2020; Reyers et al., 2017). EVs for global change and EVs for global boundaries of a Safe Operating Space for Humanity have been recommended (Plag and Jules-Plag, 2020). Work has also been progressing on Integrated EVs for Sustainability (Lehmann et al., 2020a), Essential Socio-Economic System Variables (Lehmann et al., 2020a), EVs for the food-water-energy nexus (Mccallum et al., 2020), Essential Drylands Variables (Wu et al., 2021), and Essential Ecosystem Services Variables (Balvanera et al., 2022).

Building on this growing body of EV work, the Essential Social-Ecological Variables (ESEV) approach developed here offers a more integrated framework, drawing on both systems thinking (Arnold and Wade, 2015; Forrester, 1992; Liu et al., 2007, 2015) and relationality (Haider et al., 2021; West et al., 2020). A system is defined as "a set of things—people, cells, molecules, or

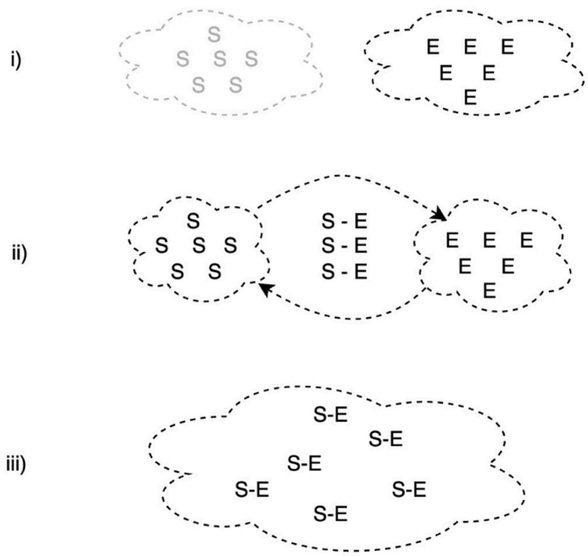

Fig. 1. Representations of how the framing of social (S), ecological (E), and social-ecological (S–E) processes in research, described by Haider, Schlüter, Folke, & Reyers (Haider et al., 2021), manifest in Essential Variable (EV) approaches. In conceptualization (i), the 'E' and 'S' are seen as separate processes. In conceptualization (ii) the 'E' system and the 'S' system, are each measured separately, with several interactions between them which are also measured. In conceptualization (iii) the focus is on data that is produced through the coevolution of 'S-E' relations.

whatever—interconnected in such a way that they produce their own pattern of behavior over time" (Meadows, 2009)(p.2). Systems thinking refers to "a set of synergistic analytic skills used to enhance the ability to identify and understand systems, predict their behaviors, and modify them to achieve desired outcomes"(Arnold and Wade, 2015)(p.7). It involves three key aspects: elements (in this case, the ESEVs that are critical for capturing the features, processes, and interactions driving SES dynamics over time and space), interconnections (how these ESEVs relate to and influence one another), and a function or purpose (here, identifying essential variables for monitoring the sustainability of a complex SES case study). Systems thinking transcends disciplinary boundaries, highlighting how interconnected elements within systems drive complex outcomes (Arnold and Wade, 2015). However, despite its emphasis on social-ecological interconnections, systems thinking often treats 'social' and 'ecological' entities as separate analytical categories, perpetuating a human-nature divide (Liu et al., 2007; West et al., 2020). By merging systems thinking principles, with a relational perspective (expanded on in section 1.2 below), this study aims to bridge the human-nature divide and emphasize dynamic social-ecological relationships as drivers of system patterns and behaviors (Garcia et al., 2020; Reyers et al., 2022; West et al., 2020).

1.2. The effect of different conceptualizations of social ecological systems on integrated monitoring and Essential social-ecological System Variables

There are different conceptualizations of SESs in the literature (Fig. 1). Early EVs work focused largely on ecological variables as separate entities as per Fig. 1 (i) (Bojinski et al., 2014; Hayes et al., 2015; Pereira et al., 2013). Recent studies measure the ecological and social systems separately, while also recognizing and measuring their interactions, as outlined in Fig. 1 (ii) (Lehmann et al., 2020a; Pacheco-Romero et al., 2020). This paper moves the selection of EVs towards Fig. 1 (iii) by focusing on data generated through the coevolution of social-ecological relations. In this dynamic process, entities, interactions, and processes within the SES mutually influence each other's development, leading to novel outcomes (Haider et al., 2021; Waring et al., 2015).

The bases for Fig. 1 (iii) are that the 'social' and 'ecological' aspects of an SES cannot readily be separated, that 'social' and 'ecological' separations are artificial, and that you cannot construct the system as a sum of its 'social' and 'ecological' parts, as the SES whole is not equal to a sum of the parts. These are central insights in the SES literature and in systems thinking and analysis more broadly (Meadows, 2009; Preiser et al., 2018).

This conceptualization shifts from a perspective that focuses on the distinct parts of a system, to a relational perspective where the dynamic relations between system components are seen as the drivers of emergent patterns and behaviors (Garcia et al., 2020; Reyers et al., 2022; West et al., 2020). Complex adaptive systems are constituted relationally, and it has been argued that the focus of SES analysis should shift away from distinct, independent objects to the dynamic relationships between social and ecological objects (Reyers et al., 2022). The ESEV process identifies data focused on where the social and ecological interact. This conceptualization affects the EV selection criteria, and the resulting EVs (discussed further in the results and discussion section).

1.3. Differentiating this study from other integrated Essential Variable work

This study sets itself apart from other integrated EV work by taking a relational perspective to monitor social-ecological relations for comprehensive characterization of social-ecological sustainability. While previous studies typically analyze social and ecological aspects separately before examining key interactions (Fukui et al., 2021; Lehmann et al., 2020a; Pacheco-Romero et al., 2020), this research fills a gap in cross-thematic EV identification by adopting a holistic approach (Lehmann et al., 2020b).

While this research was informed by a study that developed a general conceptual reference list of variables for monitoring SESs without a defined monitoring scale (Pacheco-Romero et al., 2020), as well as previous EV frameworks primarily applied at global, regional, or national levels (e.g., Kussul et al., 2020; Constable et al., 2016; Bojinski et al., 2014; Pereira et al., 2013), it is rooted in a case study at the catchment scale. Collaborating with a transdisciplinary team actively engaged in the catchment, this study addresses the need for context-sensitive monitoring, shaping the emerging contextual framing of variables. Possible reasons why an SES EV approach has not previously been applied at catchment scale include that (i) EVs work has largely been based on EO data which is available at national or global scales, (ii) Integrated EVs & the application of EVs with data that are not EO-based is a fairly new area of research, and (iii) there is lack of process for use in this kind of case study and at this scale meaning that a concerted effort in methodological development and innovation needed to be done for implementation.

By addressing overarching issues of context-dependence and scale-dependence highlighted in prior research (Pacheco-Romero et al., 2020), this paper outlines steps to apply the ESEV approach in diverse contexts. The need for an integrated SES essential monitoring approach at catchment scale arose from a transdisciplinary social-learning process (Itzkin et al., 2022), echoing broader calls in SES research to innovate methods for assessing sustainability outcomes (Selomane et al., 2019). This approach offers broad applicability across various SES landscapes, aiding in overcoming methodological and theoretical barriers to SES monitoring to inform decision-making toward sustainable development.

2. Material and methods

2.1. Case study context

2.1.1. Tsitsa River Catchment and Tsitsa Project case study

The Tsitsa River Catchment (TRC) is located in the Eastern Cape province of South Africa (Fig. 2). The catchment is characterized by steep topography and erodible soils, resulting in the formation of extensive gullies (le Roux and van der Waal, 2020). There are 2 types of rural landholdings, private and communal. The private land is primarily made up of commercial agriculture and commercial forestry (Rowntree et al., 2018). Much of communal land was cleared and tilled for cultivation during Apartheid (Rowntree et al., 2018). The communal land (found in the eastern part of the catchment, shaded in yellow on Fig. 2), is where most of the catchment's population reside, and coincides with more erodible soils (Van Der Waal et al., 2018). Residents rely, to an extent, on natural resources (Sigwela et al., 2017). Livestock holds cultural and financial value to residents (Van Der Waal et al., 2018). The catchment is a tributary of the Mzimvubu River, the last large, undammed river in South Africa. Proposals for a water resource development including 2 dams in the catchment have been put on hold because high sediment yields as a result of ecological and social issues would render a dam inoperable within 55 years (le Roux, 2018).

Between 2014 and 2023, the catchment was home to a social-ecological project, called the Tsitsa Project (TP), funded by the South African Department of Forestry, Fisheries and the Environment (DFFE). In the TP, interdisciplinary researchers, natural resource managers and residents collaborated, with the objective "to support sustainable livelihoods for local people through integrated landscape management that strives for resilient social-ecological systems, and which fosters equity in access to ecosystem services" (Van Der Waal et al., 2018) (p.18) in the upper TRC.

2.1.2. Integrated monitoring of the Tsitsa River Catchment (TRC)

The TP adopted an explicit SES approach, employing transdisciplinary research-praxis to enhance the catchment's landscape and sustainable livelihoods. Emphasizing integration across social and ecological domains, the project had a dedicated team focused on participatory monitoring, evaluation, reflection, and learning (PMERL). While PMERL facilitated the selection of biophysical and social indicators, calls from within the project prompted a move towards a more integrated understanding and streamlined monitoring system (Itzkin et al., 2022). This began with building an integrated understanding of SES drivers of degradation in the catchment (Itzkin et al., 2021), followed by exploring challenges around integration and integrated monitoring in SES research (Itzkin et al., 2022). The key focus of this paper is identifying ESEVs crucial for understanding and managing 'the system'. This question is

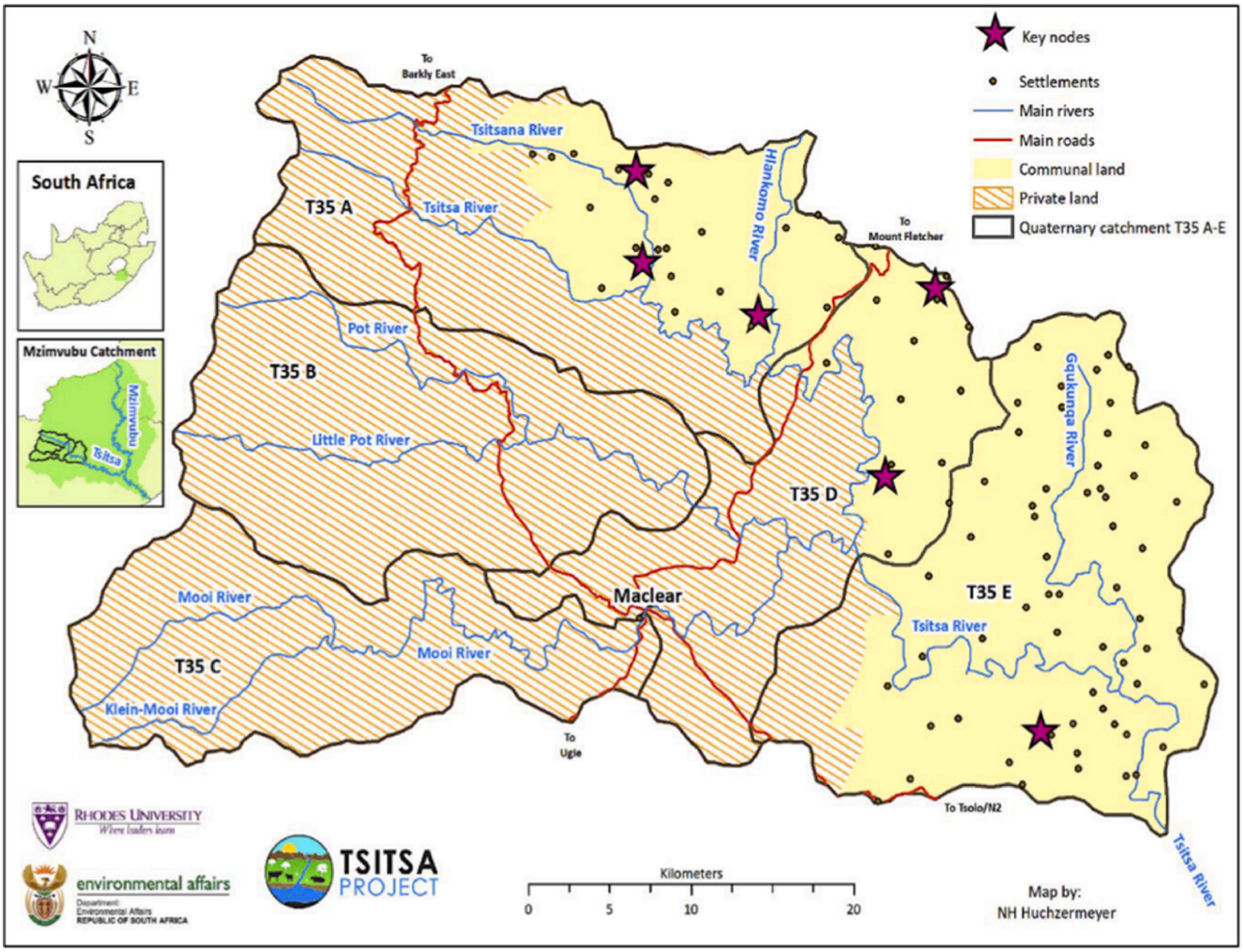

Fig. 2. Map of the Tsitsa River Catchment by N.H. Huchzermeyer. The Tsitsa Project focused on the upper catchment, which coincides with the communal land where most of the catchment population resides and where soil erosion and land degradation are most severe.

context-specific and depends on a project's management objectives or goals.

2.2. Methods: A systemic transdisciplinary social learning process

A transdisciplinary social learning approach was employed, involving representatives from all TP Communities of Practice, the internal decision-making team of the TP at Rhodes University, and stakeholders from diverse transdisciplinary organizations including research institutions, NGOs, government funders, and implementers. The data collection process comprised of iterative rounds of stakeholder engagement and analysis, divided into three phases, incorporating the principles of systems thinking (Forrester, 1992; Liu et al., 2007, 2015) into a transdisciplinary problem-solving process.

2.2.1. Phase one: Developing candidate essential social-ecological System Variables and indicators

The research commenced with scoping interviews (n = 19) conducted with various TP research-praxis team members. These interviews gathered data on the key issues that require monitoring and the current state of monitoring within the catchment (coded as 'I1'). The interview data underwent thematic analysis (Braun and Clarke, 2006; Clarke and Braun, 2014). This was followed by a review of internal project documentation (coded as 'D') and two workshop sessions (coded as 'W1'—n = 29, & 'W2'—n = 17), where systems modelling (Forrester, 1980; Meadows, 2009) and activity systems modelling (Engeström, 1987, 2001; Ploettner et al., 2016) techniques were utilized to depict key issues in the system. More details on the overall research process, can be found the materials and

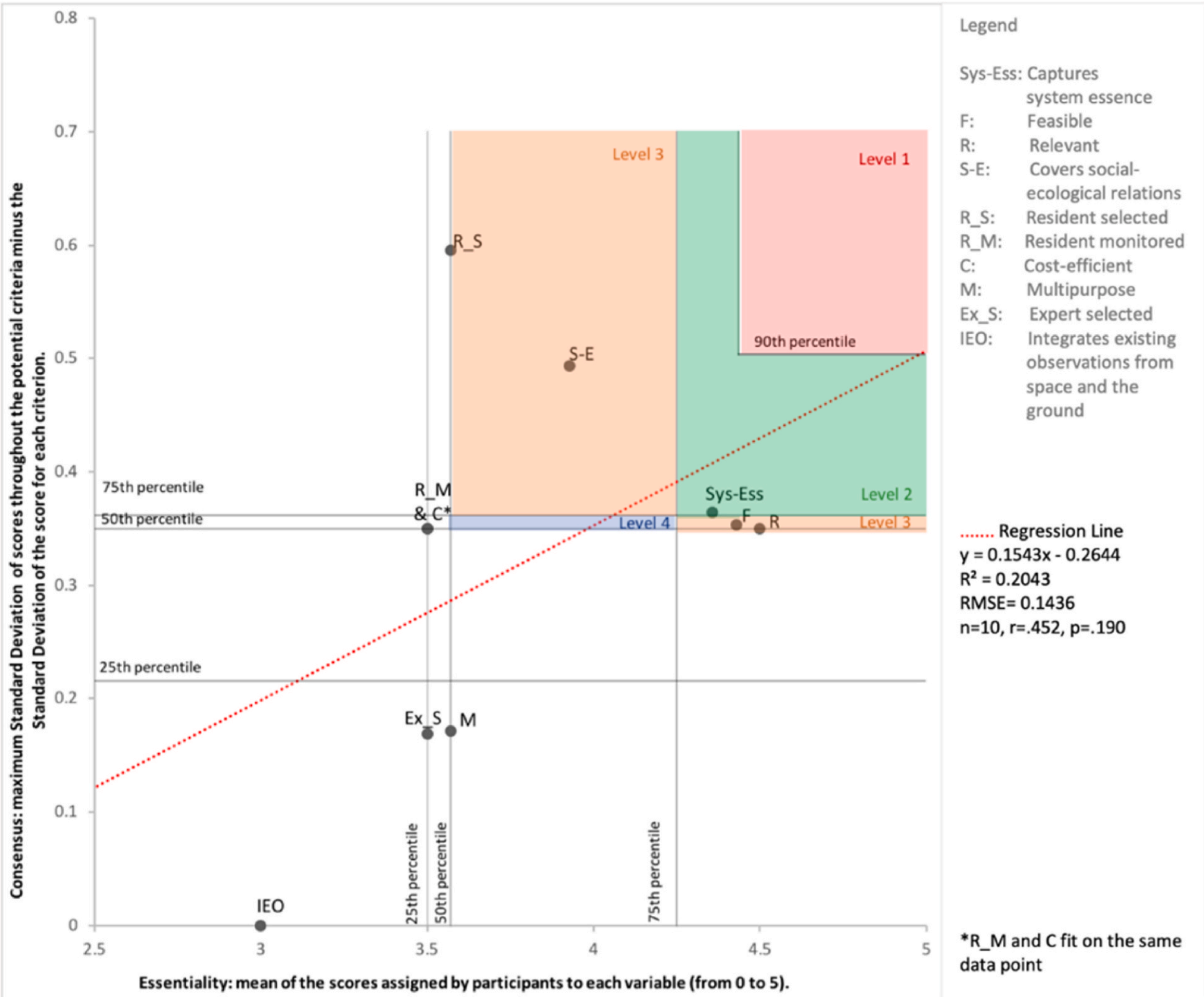

Fig. 3. Selection Criteria for Essential Social-Ecological System Variables by priority in terms of essentiality (mean of the scores assigned by experts to each criterion), as well as the level of consensus (estimated as the difference between the maximum standard deviation of the scores for all potential criteria) around the essentiality assigned by the transdisciplinary Tsitsa Project research-praxis team (n = 14). The legend appears on right of the figure. Below the legend, the equation of the regression line, the significance of the line slope (p-value) and the root-mean-square error (RMSE) are indicated, as are the number of variables (n), the Pearson's correlation coefficient (r), and its significance (p-value).

methods section in Itzkin (2024).

A list of 10 potential selection criteria to filter the candidate ESEVs were derived based on EV literature (Fukui et al., 2021; Reyers et al., 2017; Scholes and Biggs, 2005; Wu et al., 2021) and TP values and principles, particularly around community participation, which emerged strongly from phase one (Appendix A; Table A.1).

A list of candidate ESEVs and indicators were derived from data on key issues and monitoring variables from Phase 1 (I1, D, W1 & W2), along with six biophysical and seventeen social indicators previously selected through expert-driven disciplinary processes within the project (Appendix A; Table A.2). This resulted in a preliminary list of variables and indicators potentially important for capturing key features, processes, and interactions driving the dynamics of the social-ecological system. These candidate ESEVs and indicators were then cross-referenced with variables and indicators from the broader SES and EV literature (Appendix A; Table A.2). This cross-referencing acted as an additional filter, ensuring not only that the selected variables were contextually relevant but that they had also undergone critical evaluation in previous research.

2.2.2. Phase two: gathering input to prioritize criteria and variables

In phase two, a Google Form survey (coded as 'S') was developed incorporating potential selection criteria, and candidate variables and indicators identified in phase one. The survey (Appendix B) introduced ten potential selection criteria for variable prioritization and asked participants to score each criterion from 0 (non-essential) to 5 (most essential). Participants were also asked to score each candidate social-ecological variable and indicator and provide comments and suggestions.

The survey was completed by 14 participants with diverse expertise from biophysical, technical, and social fields, ensuring a holistic approach to the project's goals. This group includes researchers in charge of biophysical monitoring, restoration, social monitoring, knowledge and learning coordination, participatory governance, and integrated planning. Also included are project

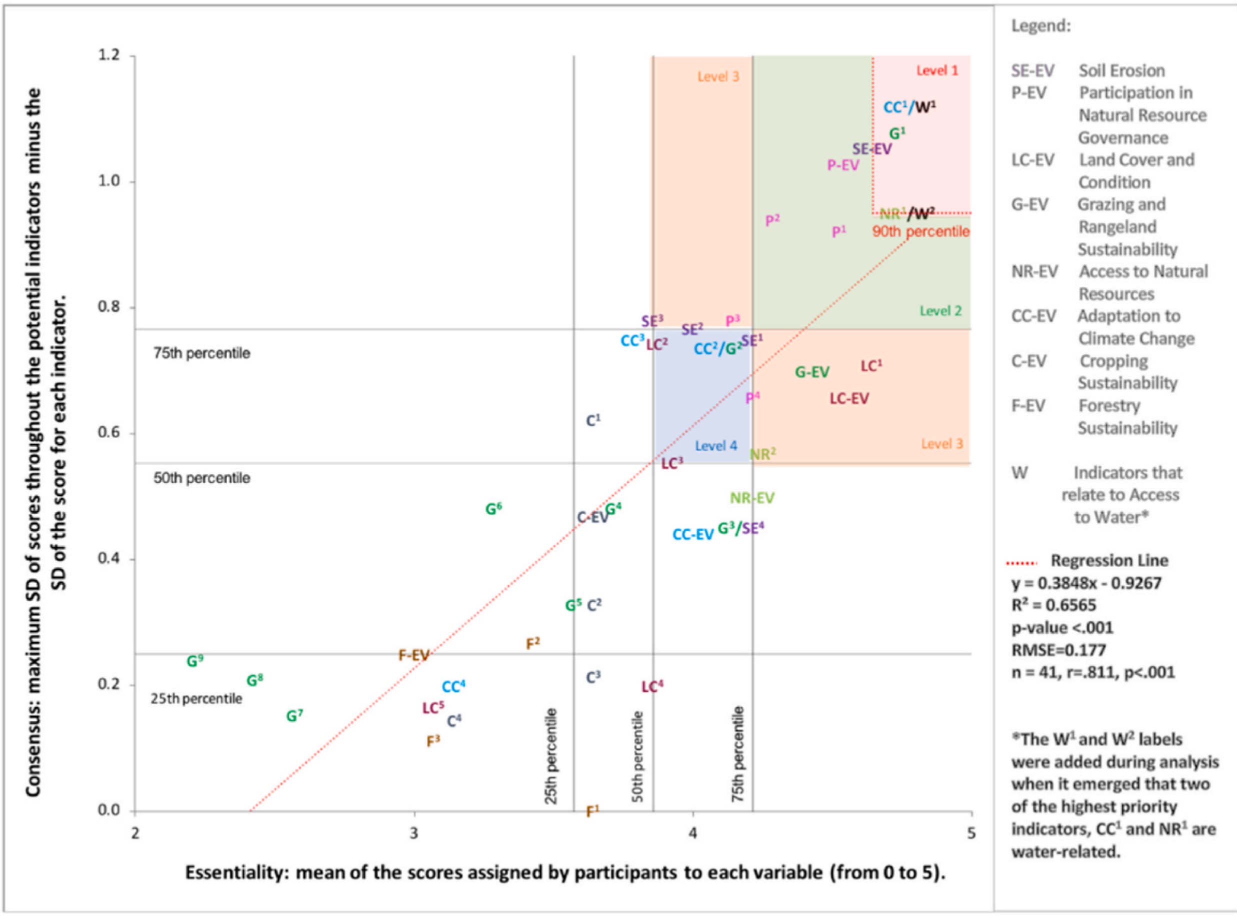

Fig. 4. Essential Variable (EV) themes and associated indicators by priority in terms of essentiality (mean of the scores assigned by experts to each variable), as well as the level of consensus (estimated as the difference between the maximum standard deviation of the scores for all candidate variables and associated indicators) around that essentiality assigned by the transdisciplinary Tsitsa Project research-praxis team (n = 14) (links with the indicators listed in Tables 1 and 2). The legend appears on right of the figure. Below the legend, the equation of the regression line, the significance of the line slope (p-value) and the root-mean-square error (RMSE) are indicated, as are the number of variables (n), the Pearson's correlation coefficient (r), and its significance (p-value).

leaders, a field coordinator, and a representative from the Department of Forestry, Fisheries, and the Environment, which funded the project. Input from this diverse range of participants provides transdisciplinary insights and perspectives on SES sustainability and monitoring.

2.2.3. Phase three: prioritization of variables and indicators

In phase three, survey results (n = 14) were used to conduct two "essentiality vs. consensus" analyses (based on the 'relevance vs. consensus' analysis conducted by Pacheco-Romero et al., 2020). The first analysis focused on the selection criteria for ESEVs for the TRC ('essentiality vs. consensus' a), while the second analysis addressed variables and indicators for monitoring the TRC ('essentiality vs. consensus' b).

'Essentiality' in this study refers to the importance participants assign to (a) selection criteria, and (b) variables and indicators in relation to the ESEV selection criteria for the TRC and TP context. Consensus was estimated as the difference between the maximum standard deviation of the scores found throughout the (a) 10 potential selection criteria, and (b) 44 candidate variables and indicators, and the standard deviation of the score for each criterion, variable, or indicator (low differences indicate low consensus and high differences indicate high consensus).

Essentiality and consensus scores were placed on scatter plots (Figs. 3 and 4), and were ranked into five categories based on their percentile, with four categories of priority levels and one non-priority category. Priority level 1 (top priority) included variables with essentiality and consensus above the 90th percentile; level 2 included variables between the 75th and 90th percentiles; level 3 included variables with essentiality above the 75th percentile but consensus between the 50th and 75th percentiles and vice versa; and finally, level 4 included variables with essentiality and consensus between the 50th and 75th percentiles. The nonpriority category included variables with essentiality and consensus below the 50th percentile. Regression analyses were performed to understand the correlation between essentiality and consensus.

To assess potential biases and gaps in the list of variables, the additional suggestions and comments provided by researchers in the survey were analyzed. Comments and suggestions were themed, and recurrent themes (addressed five or more times by respondents) were identified as potential additional ESEVs. The results were discussed at a third participatory workshop (coded as 'W3', n = 7).

Finally follow up expert interviews were conducted for themes where further input was required (coded as 'I2.1-I2.5', n = 5).

Utilizing interviews, surveys, and participatory workshops, iteratively throughout the research process facilitated the analysis of issues using multiple methodologies, as per Roe's (1998) recommendation, and promoted new knowledge exchange from social learning (Reed et al., 2010).

3. Results

3.1. Proposed Essential social-ecological system Variable selection criteria for Tsitsa River Catchment

The selection criteria for the development of EVs for SESs must take the values and goals of those working in a particular system into consideration. Participants proposed the most suitable selection criteria for ESEVs for their context. 'Captures System Essence' (Reyers et al., 2017) emerged as the highest priority selection criterion (level 2, Fig. 3), followed by 'Relevance', 'Feasibility', 'Covers Key Social-Ecological Interactions' (inspired by (Haider et al., 2021; Schlüter et al., 2019; Wu et al., 2021) and 'Resident Selected' (level 3, Fig. 3). The TP has included catchment residents in the development and operationalization of its monitoring system, where possible. Participants expressed the desire for the monitoring system to consider what catchment residents want to monitor and how to do so (I1). While getting direct input on the selection of the ESEVs and indicators from residents was not possible in this process, resident input from project documents and community meetings was reviewed and taken into consideration. This resident input is important because even if it is apparently in conflict with what is most efficient or cost-effective, it could be important to improve long-term engagement and sustainability.

The selection criteria for the ESEVs are defined as follows:

1. Captures System Essence: represents the key features, processes and interactions driving SES dynamics over time and space (Reyers et al., 2017);
2. Relevance: indispensable/foundational for tracking the system;
3. Feasibility: the state or degree of being easily or conveniently done within the context of the specific cultural, economic and social norms of the system of interest; and
4. Covering Key Social-Ecological Relations or Interactions: data that is co-produced by the social and ecological domains (inspired by (Haider et al., 2021; Schlüter et al., 2019; Wu et al., 2021).

Drawing from the selection criteria above, the definition of ESEVs is: the minimum set of critical social-ecological variables to capture key features, processes and interactions driving SES dynamics over time and space.

3.2. Essential social-ecological System Variables and indicators for the Tsitsa River Catchment

Four social-ecological themes: 'sustainable livelihoods', 'natural resource governance', 'human impacts on the environment', and 'climate change adaptation' were identified. Within these themes, a list of eight candidate ESEVs and thirty-three potential indicators was developed. Analysis of the candidate ESEVs and indicators in the survey revealed a significant positive relationship (n = 41, r =

0.811, $p < .001$) between the average essentiality for characterizing and monitoring SESs obtained for each variable and the consensus observed across respondents (Fig. 4). By applying the prioritization thresholds, four candidate ESEVs— 'soil erosion related to human actions on the land' (SE-EV), 'participatory natural resource governance' (P-EV), 'grazing and rangeland sustainability' (G-EV), and 'land cover and condition' (LC-EV)—and fifteen indicators were considered priority (Table 1)].

Priority variables 'soil erosion'(SE-EV), and 'participatory natural resource governance' (P-EV) were associated with priority indicators. Non-priority variables 'sustainable cropping' (C-EV) and 'sustainable forestry' (F-EV) were associated with non-priority indicators. 'Land cover and condition' (LC-EV), 'sustainable grazing and rangeland'(G-EV), 'access to natural resources' (NR-EV) and 'climate change adaptation (CC-EV)' comprised of a combination of priority and non-priority variables and indicators. This may be related to the theoretical nature of the of the EV themes versus the practical nature of indicators. Other possible reasons for this are outlined within the relevant ESEVs sub-sections below.

Six of the sixteen priority indicators were duplicated to monitor more than one ESEV (as indicated with * in Table 1). The 'duplication' shows that a particular indicator is 'multi-purpose' which was a potential selection criterion (Fig. 3) as it could be a desirable attribute for streamlined monitoring. Data on 'duplicated' indicators could be collected once, but analyzed differently for different themes, thus simplifying monitoring. This effectively reduces the number of priority indicators for monitoring.

The following sub-sections (3.2.1-3.2.8) present the combined analysis of the ESEV and indicator results from the 'essentiality vs. consensus' analysis of survey data (Fig. 4), the additional suggestions and comments provided by participants during different stages of the research process, as well as how the study context determines priority. The presentation of the results in relation to the context highlights the importance of context to guide appropriate monitoring. The ESEVs are positioned in descending order from the higher to lower priority for the TRC. Variables considered non-priority for the TRC (3.2.5–3.2.8) have been included because they may hold priority status in different contexts and could serve as potential inputs when conducting the ESEV process elsewhere.

3.2.1. Soil erosion, related to human actions on the land (priority level 1)

The Tsitsa catchment's duplex, dispersive soil structure makes it prone to soil erosion, which is exacerbated by various interconnected social and ecological factors (Itzkin et al., 2021; le Roux and van der Waal, 2020). The TP aims to mitigate soil erosion through integrated land use management, identifying it as a level 1 priority ESEV within the catchment. The three priority indicators (level 3): soil erosion by anthropogenic practices (SE^1), mass stabilization and control of erosion rates (SE^2), and soil erosion as an ecosystem disservice (SE^3), were based on the social-ecological literature (Pacheco-Romero et al., 2020; Shackleton et al., 2016) and could be measured across the catchment using earth observation.

However, challenges were noted in measuring SE^1 due to its complex nature, and SE^2 due to its temporal scale being out of sync with project timelines (S & I2.3). To address this, percentage vegetation cover (already being monitored in themes 3.2.3 and 3.2.4) and percentage bare soil were proposed as proxies for soil erosion (S, W3 & I2.2). Suspended sediment monitoring, already in place in the catchment (Bannatyne et al., 2022), was unanimously agreed upon as an essential indicator for assessing how much soil is leaving the system as the result of both natural and anthropogenic erosion, aligning with the TP's goal of reducing sediment through improved land management (W3). Remote sensing for land cover was also suggested as a potentially more efficient method for assessing erosion rates in the context of sustainable land management (I2.3).

3.2.2. Participation in natural resource governance (priority level 2)

Participation in natural resource (NR) governance emerged as a priority ESEV (level 2), with all proposed indicators considered essential (S). This aligns with the TP Governance Community of Practice's emphasis that participatory governance development underpins the likelihood of biophysical restoration delivering ecological and societal benefits (Palmer et al., 2022). Overall 'land user participation' in NR governance structures (P^1, level 2) was highlighted as more significant than 'women and youth participation' (P^4, level 4). This could be because exclusion from structures is widespread in the catchment's rural community (I2.4). The participation indicators are suggestive of the relevance and potential effectiveness of governance processes in stimulating participation (I2.4).

Regarding 'land user satisfaction with their representation in decision-making and planning processes' (P^3, level 3), a household survey conducted in 2023 ($n = 178$) revealed that most catchment residents do not desire increased representation. A range of factors could be behind this. It is possible that pushing people to participate in NR governance may be counter-cultural and could create unnecessary change resistance (I2.4). It is important to have an adaptive approach that takes consideration of feedback like the above, and to relate monitoring to the high-level goal (in this case social-ecological sustainability), rather than focusing on achieving some kind of imposed metrics.

To monitor participation in NR governance, a shift from annual household surveys to specific interventions, such as assessing participation and progress within grazing associations, was suggested (I2.4). This approach aims to analyze meaningful participation linked to relevant livelihood themes, moving beyond general participation to meaningful engagement in the context.

3.2.3. Grazing and rangeland sustainability (priority level 3)

The sustainability of grazing and rangelands are interconnected, with uncontrolled grazing and overgrazing identified as key drivers of degradation in the catchment Click or tap here to enter text. Positioned within the sustainable livelihoods layer, this ESEV highlights the importance of sustainable livestock and grazing practices for improving social-ecological sustainability.

Survey participants identified 'rangeland condition' (G1, level 1) as the sole essential indicator for monitoring rangeland and grazing sustainability in the catchment. A related priority indicator, 'interventions to manage the grassland' (CC2/G2, level 4), emerged from the climate change adaptation theme. All other 'grazing and rangeland' indicators were deemed non-priority (S), prompting consideration of the effectiveness of the chosen priority indicators for tracking grazing and rangeland sustainability.

Table 1
List of prioritized social-ecological variables and associated indicators for the Tsitsa River Catchment. The list is structured into 6 social-ecological variables associated with priority indicators. Priority level 1 have relevance and consensus scores above the 90th percentile; level 2 includes variables with both values between the 75th and 90th percentile; level 3 contains variables where relevance was above the 75th percentile and consensus between the 50th and 75th percentiles and vice versa; and finally, level 4 includes those variables with relevance and consensus between the 50th and 75th percentiles. Potential additional indicators from the bias and gaps analysis appear in the last column, in italics.

Essential Social-Ecological Variable Theme	Essential Social Ecological Variable and Priority Level.	Associated Priority Indicators by level				*Potential additions with that emerged from gaps and bias analysis of participant input.*
		Priority 1	Priority 2	Priority 3	Priority 4	
Human Impacts on the Environment	Soil Erosion (related to human actions on the land) (SE-EV) **Priority 1**			SE^1: Soil erosion by anthropogenic practices SE^2: Mass stabilization and control of erosion rates SE^3: Soil erosion as an ecosystem disservice		*SE^4/G^3: Percentage vegetation or ground cover*[a] *SE^5: Suspended sediment concentration*
	Land Cover and Condition (LC-EV) **Priority 3**			LC^1/G^1: Grassland condition[a]	LC^2: Land cover change LC^3: Woody invasive species cover	
Governance	Participatory Natural Resource Governance (P-EV) **Priority 2**		P^1: Land user participation in natural resource governance structures	P^2: Participation in sustainable land-use management practices P^3: Land user satisfaction that their voices are represented in decision making and planning processes	P^4: Women and youth participation in natural resource governance structures	*P^5/CC^5: Participatory governance, management or decision-making around climate change adaptation*[a]
Sustainable Livelihoods	Sustainable Grazing and Rangelands (G-EV) **Priority 3**	G^1/LC^1: Rangeland condition[a]			G^2/CC^2: Interventions to manage the grassland[a]	*G^3/SE^4: Percentage vegetation or ground cover*[a] *G^{10}: Willingness to practice sustainable grazing* *G^{11}: Fire Regime*
	Priority indicators associated with Access to Natural Resources (NR-EV) **Non-Priority**	NR^1/W^2: Access to potable water[a]		NR^2: Access to natural resources by sub-category (food types and sources, firewood, thatch, medicinal plants, sand for building)		
Climate Change Adaptation	Priority indicators associated Climate Change Adaptation (CC-EV) **Non-Priority**	CC^1/W^1: Interventions to store, capture and protect water[a]			CC^2/G^2: Interventions to manage the grassland[a]	*CC^5/P^5: Participatory governance, management or decision-making around climate change adaptation*[a]

[a] Duplicated indicators identified as cross-cutting or multi-purpose, could monitor multiple Essential Social-ecological System Variables.

Table 2
Variables and indicators considered non-priority for monitoring in the Tsitsa River Catchment in relation to the goals of the Tsitsa Project, but which may be higher priority in other contexts.

Theme	Social-ecological Variable theme	Non-Priority Indicators
Climate Change Adaptation	Climate Change Adaptation (CC-EV) (Non-Priority)	CC^3: Interventions to grow climate smart crops CC^4: Interventions to alleviate heat stress (for humans and livestock)
Sustainable Livelihoods	Non-priority indicators associated with 'Sustainable Grazing and Rangelands' (G-EV) (a priority 3 ESEV)[a]	G^3: Vegetation cover G^4: Livestock management G^5: Livestock density G^6: Income related to sustainable livestock livelihoods G^7: Sales rates of agricultural products G^8: Livestock theft G^9: Livestock ownership patterns
	Sustainable Cropping (C-EV) (Non-Priority)	C^1: Income from sustainable cropping livelihoods C^2: Ratio between crop land with sufficient ground coverage and total crop land C^3: Proportion of agricultural area under productive and sustainable agriculture C^4: Cropland production
	Sustainable Forestry (F-EV) (Non-Priority)	F^1: Progress towards sustainable forest management (methods of forestry) (non-priority) F^2: Forest area as a proportion of total land area (non-priority) F^3: Income from sustainable forestry products (non-priority)

[a] Sustainable Grazing and Rangelands is an exception in this table in that, while it is a priority variable, it is associated with several non-priority indicators.

Rangeland condition (G^1) in the catchment has been monitored along selected transects, facilitated by local eco-rangers (Huchzermeyer et al., 2021; Huchzermeyer, N; Schlegel, P; van der Waal, 2019), but faces challenges due to the need for skilled technicians proficient in species identification and the method's limitations in detecting changes over large areas. Simplified transect assessments focusing on basal cover of dominant life forms, along with catchment-scale vegetation cover monitoring using remote sensing, were proposed as alternative approaches for areas like the TRC (W3, I2.1).

Grazing associations support coordinated rangeland management, offering avenues for monitoring livestock management and density (Huchzermeyer et al., 2021). Additional indicators suggested (W3) include community willingness to implement grazing management practices, monitored through grazing association membership or household surveys, and fire regime monitored using remote sensing methods (Moderate Resolution Imaging Spectroradiometer (MODIS), Normalized Difference Vegetation Index (NDVI), Scar Maps, or the Advanced Fire Information System (AFIS)). Fire regime, though initially omitted from surveys, was deemed essential due to its link with rangeland condition and overgrazing, particularly in light of predicted climate change impacts (Snyman, 2020, W3 & I2.1). Community reports of arson further underscore the social-ecological implications of fire management.

3.2.4. Land cover and condition (priority level 3)

Land cover and condition emerged as a level 3 priority ESEV. 'Grassland condition' (LC^1, level 3) was rated highest among potential indicators, which overlaps with the highest scoring indicator from the grazing and rangeland theme. Other essential indicators included 'land cover change' (LC^2, level 4), and 'woody invasive species cover' (LC^3, level 4). The TP focused its land cover and condition assessment on woody invasive species cover and erosion, establishing a digitized baseline for monitoring purposes (I2.2). While 'land cover change' (LC^2) is considered valuable for assessing landscape impacts, the TP has not specifically examined this aspect (I2.2, Biophysical Monitoring Report/s). Like many other countries, South Africa offers freely available land cover datasets updated every 2–5 years, providing broadscale insights into catchment-scale changes (https://egis.environment.gov.za/data_egis/data_download/current; most recent time interval 2020). Regarding 'woody invasive species cover' (LC^3), its ecological impact is negative, but its social-ecological implications are complex, necessitating social data on the value and utility (ecosystem services and disservices) of these species to communities.

3.2.5. Access to natural resources (non-priority)

The TP's overall objective includes 'fostering equity in access to ecosystem services' (Van Der Waal et al., 2018). Given the high levels of poverty and unemployment, as well as the rural nature of the catchment; there is a high reliance on natural resources, making 'access to natural resources' (NR-EV) a seemingly critical variable (S). It was therefore surprising that there was a lack of consensus around the overall importance of NR-EV as an ESEV. While both the proposed indicators were deemed essential (Table 1), 'access to potable water' (NR^1) was highlighted as more of a priority (level 1) than 'access to natural resources' (NR^2, level 3). The NR^2 indicator can be broken down into sub-categories (such as food types & sources, firewood, thatch, medicinal plants, water from the natural environment, and sand for building) depending on relevance. Participants also suggested considering monitoring the condition, management, and sustainable utilization of these natural resources (S). These data were proposed to be collected via annual household surveys.

3.2.6. Climate change adaptation (non-priority)

Climate change adaptation initiatives recently started gaining traction in the catchment, with the TP conducting workshops for local government and developing climate change learning resources for monitors (Kotschy and Mvulane, 2020). The TP devised climate change adaptation indicators to monitor the outcomes of sustainable land management and livelihood interventions in the catchment (Rowntree, 2020). In the survey, climate change adaptation (CC-EV) was presented as a potential ESEV alongside indicators proposed by Rowntree (2020). While climate change adaptation emerged as a non-priority ESEV overall, two indicators stood out: 'interventions to store, capture, and produce water' (CC1), rated as the highest priority indicator (level 1), and 'interventions to manage the grassland' (CC2), rated as another priority indicator (level 4). These indicators align with other themes, 'access to water' and 'grazing and rangeland sustainability'. Household surveys could be utilized to monitor these climate change adaptation indicators by counting the number of reported interventions implemented by households.

3.2.7. Cropping sustainability (non-priority)

Cropping sustainability (C-EV) and all the associated potential indicators (C^1, C^2, C^3 & C^4) were considered non-priority variables in the context (S). Monitoring cropping as an indicator of sustainable livelihoods related to project interventions in the TRC is tricky because cropping (including home gardens) in the communal areas is highly rain dependent (W3). Due to the past Apartheid policies vast areas in the catchment were contoured, but for various reasons are not suitable for cropping and remain largely unplanted. In the context of the TP, grazing on disused fields came up as a contributor of erosion due to a lack of grazing management (Itzkin et al., 2021). Interventions to address this could be monitored within the 'sustainable grazing and rangelands' theme (3.2.3).

3.2.8. Sustainable forestry (non-priority)

Sustainable forestry (F-EV) and all proposed forestry indicators (F^1, F^2 & F^3) were considered non-priority for communal land in the catchment (S). Workshop participants indicated that forestry currently does not represent key features, processes, or interactions driving the social-ecological system dynamics of the catchment (W3). Most forestry land in the catchment is privately managed without strong connections to sustainable livelihoods, integrated landscape management, or equitable access to ecosystem services in communal lands. While some social and livelihood aspects related to woodlots were acknowledged, forestry was generally not seen as an ESEV (S & W3). It's worth noting that forestry's status as an ESEV could change, especially if initiatives such as the Forestry Master Plan to plant seven-hundred-thousand trees in the Eastern Cape were to materialize (DTIC, 2020).

3.3. Additional potential Essential social-ecological System Variables for the Tsitsa River Catchment that emerged during the research process

Three new potential ESEVs emerged during the survey process. The first is 'access to water', the second relates to the 'local NR governance system', and the third pertains to 'human well-being in the TRC' (Table 3). Although further engagement would be required to refine, finalize, and prioritize these ESEVs, they represent additional potential avenues for enhancing the understanding of the complex social-ecological dynamics within the TRC and beyond, which should be considered for future monitoring and research efforts.

3.3.1. Access to water (proposed addition 1)

Access to water was not initially included in the survey but emerged strongly as a potential addition during the gap analysis (Table 3). Two of the highest priority indicators identified in the survey, "interventions to capture, store, and protect water" (CC1/W1) and "access to potable water" (NR1/W2), are water-related (Fig. 4). Furthermore, several suggestions were made in the survey ($n = 7$) to include other water-related indicators (Table 3).

Access to safe drinking water is a top priority for catchment residents, the majority of whom collect drinking water directly from the environment, reflecting trends seen in other rural households in the Eastern Cape (Apraku et al., 2023). More than half of the household survey respondents (53.7%) reported experiencing significant periods without sufficient drinking water in the last month,

Table 3
Additional Proposed Essential Social-Ecological System Variables (ESEVs) and Indicators to monitor the Tsitsa River Catchment in relation to the goals of the Tsitsa Project, based on topics brought up 5 or more times in the survey, which were discussed at the follow-up workshop & interviews.

Theme	Additional Essential SES Variable (ESEV) Theme	Potential Indicators
Water	*Access to Water (W-EV) (n = 7)*	W^1: Interventions to store, capture and produce water (level 1, Fig. 4) W^2: Access to potable water (including source & distance) (level 1, Fig. 4) *W^3: Access to water from the environment* (including source & distance)
Governance	*Local Governance System (GS-EV) (n = 5)*	*GS^1: Accessibility of local governance actors* *GS^2: Functional institutions enabling participatory NRM governance* *GS^3: Local governance capacity* *GS^4: Land user trust in governance processes – measures procedural trust,* *GS^5: Positive collaboration of land users with governance actors – measures rational trust* *GS^6: Natural Resource Management Rules (in form and in use)*
Human Well-Being	*Human Well-being in the landscape (WB-EV) (n = 5)*	*WB^1: A 'good life in the catchment'* *WB^2: Sense of place and identity* *WB^3: Ritual value from SES*

highlighting water security concerns. Given the current climate change adaptation priorities in South Africa (Department of Environment Forestry and Fisheries, 2017), particularly in the highly vulnerable Eastern Cape region which is enormously vulnerable to changed rainfall patterns (Mahlalela et al., 2020), issues related to access to water and water-related climate change adaptation are crucial.

3.3.2. Local natural resource management governance system (proposed addition 2)

Several participants (n = 5) in the survey proposed indicators related to the 'local Natural Resource Management (NRM) governance system', suggesting its relevance as an ESEV within the context. During the follow-up workshop (W3), participants strongly recommended its inclusion as an ESEV and discussed potential indicators (GS^1-GS^6, Table 3). The most emphasized aspect for monitoring the local NRM governance system focused on the accessibility of local governance actors to land users (GS^1). This aspect can be monitored through the presence of individuals facilitating connections between local land users and landscape governance (Fry et al., 2021) & (I2.4).

3.3.3. Human well-being in the landscape (proposed addition 3)

Human well-being is a multifaceted concept, encompassing objective and subjective dimensions (King et al., 2014), which makes its integration into a streamlined monitoring system challenging. Initially excluded from the survey due to its complexity and perceived social nature (rather than social-ecological), well-being was emphasized by survey participants (n = 5) within the socio-ecological context. They highlighted dimensions of well-being relevant to the landscape, including landscape assets and livelihoods, sense of place, spiritual well-being associated with cultural sites and rituals, and identity (Table 3). Recognizing the significance of understanding human well-being for comprehending SES dynamics, they proposed framing it as 'human well-being in the TRC/landscape'. This corresponds with recent efforts to monitor well-being within a social-ecological context, acknowledging its ecological embeddedness (King et al., 2014; Sangha et al., 2015; Wali et al., 2017).

3.4. Addition of key ecological and social variables

Upon reflection, participants considered the SES variables derived from this process to be comprehensive and providing a broad overview to characterize the system in relation to the TP vision (W3). Alongside the ESEVs, a few ecological and social variables were identified as necessary for monitoring to characterize and contextualize the system. Ecologically, climate variability, particularly rainfall and hydrology, was deemed a crucial driver of SES dynamics over time in this catchment, given the high dependency of land conditions and livelihoods on climate (12). Thus, climate variability must be considered when assessing the suitability and efficacy of project interventions, especially with the increasing visibility of climate change impacts. Education, including technical education, and access to the knowledge economy were suggested as indicators of a thriving SES from a social perspective (S). This could broadly be monitored via capacity development initiatives, seen as integral to enhancing the agency of TRC residents in local governance processes (Palmer et al., 2022).

4. Discussion

The resulting list of ESEVs and associated indicators were designed as a preliminary framework, poised for continual refinement and augmentation in accordance with the iterative nature of adaptive learning processes. The conception of ESEVs was derived from a deliberate participatory selection process, guided by a relational perspective rooted in systems thinking principles, and considering spatial and temporal scales. This participatory approach ensured the contextual relevance and applicability of the chosen variables. By employing these selection criteria, a focused set of relational social-ecological variables has been distilled, serving as linchpins in understanding the fundamental drivers, processes, and interactions underpinning SES dynamics across time and space.

The proposed definition of ESEVs, encapsulating the "minimum set of critical social-ecological variables to capture key features, processes, and interactions driving SES dynamics over time and space," underscores a commitment to a holistic approach that embraces the complexity of SESs. This methodology, as informed by previous work (Haider et al., 2021; Reyers et al., 2017), sought to streamline the monitoring endeavor while simultaneously providing an encompassing and interconnected understanding of SES condition and function.

4.1. Strength of connectivity of the essential social-ecological system variables

This study used a relational conceptualization of SESs as being intrinsically connected to develop a set of variables for streamlined and integrated monitoring. The identification of cross-cutting indicators capable of assessing multiple EVs provided an early intimation of the strong connectivity of the ESEVs (Table 1). The systems model below visually illustrates the interconnectivity among various resulting ESEVs and indicators for the TRC (Fig. 5). The model follows diagrammatic conventions of a causal loop diagram, with green '+' signs indicating relations where a change in the cause creates a change in the effect in the same direction, while red '−' signs show inverse relations. Reinforcing feedback loops, numbered R1-R4, enhance whatever direction of change are imposed on them to cause vicious or virtuous cycles (Meadows, 2009). Unboxed black text shows priority indicators through which changes in the ESEVs are proposed to be monitored.

Fig. 5 was developed through an iterative approach that integrated insights from different stages of the participatory process. Some connections were initially identified during interviews, participatory workshops (W1 & W2), and surveys where stakeholders contributed based on their experiences and insights. Additional connections were identified later during a comprehensive analysis of the data gathered throughout the entire participatory process, including a follow-up workshop (W3). As a result, the diagram captures a deeper and more integrated view of the causal relationships between priority indicators and ESEVs, demonstrating how monitoring these indicators allows tracking of ESEVs and SES dynamics.

Without intervention, many of the dynamics of the TRC reinforce the system in undesirable directions to form vicious cycles. To maintain brevity, only the main features that underscore the robustness of connectivity are discussed here. The four priority ESEVs identified for the TRC are strongly interconnected: a decrease in *participation in natural resource (NR) governance* including less *participation in sustainable land-use management practices* would result in less *sustainable grazing and rangelands*, and a decrease in (intact and natural) *land cover and condition*, which increases *soil erosion* (Fig. 5).

Furthermore, the identification of several reinforcing loops (R1-R4) involving the priority ESEVs show how changes in these variables can exert a strong influence within broader feedback mechanisms that drive the SES dynamics of the TRC, making them well-suited for integrated monitoring. For example, as users attempt to extract maximum benefit from communal rangelands without effective governance, un*sustainable grazing and rangeland* practices persist, resulting in further deterioration in *land cover and condition* thereby perpetuating a vicious cycle (R1), thus driving the system in an undesirable direction. From a systemic perspective, the goal is to shift the feedback loops that have been reinforcing undesirable outcomes in the TRC, into virtuous cycles that produce desirable outcomes. This can be achieved primarily through changes in the direction of the ESEVs and can be tracked by monitoring the priority indicators. Shifting the direction of some of the reinforcing loops from vicious cycles to virtuous cycles would have a balancing effect, countering undesirable runaway effects on the system.

The three additional ESEVs that were identified through the bias and gaps analysis – *local natural resource governance system, access to water,* and *human well-being in the landscape* (Fig. 5) – are nexus points that play key roles in driving the overall SES dynamics of interest. *Human well-being in the landscape* is clearly influenced by the other ESEVs and indicators: *access to water, access to natural resources, soil erosion related to human actions on the land, land cover and condition,* and *land user satisfaction of their voices represented.* While *human well-being in the landscape* does influence other variables, these connections are complex, and well-being did not emerge from this analysis as a major direct driver of other ESEVs in the TRC.

Fig. 5 thus illustrates the highly interconnected nature of the four priority ESEVs and associated indicators that emerged from this

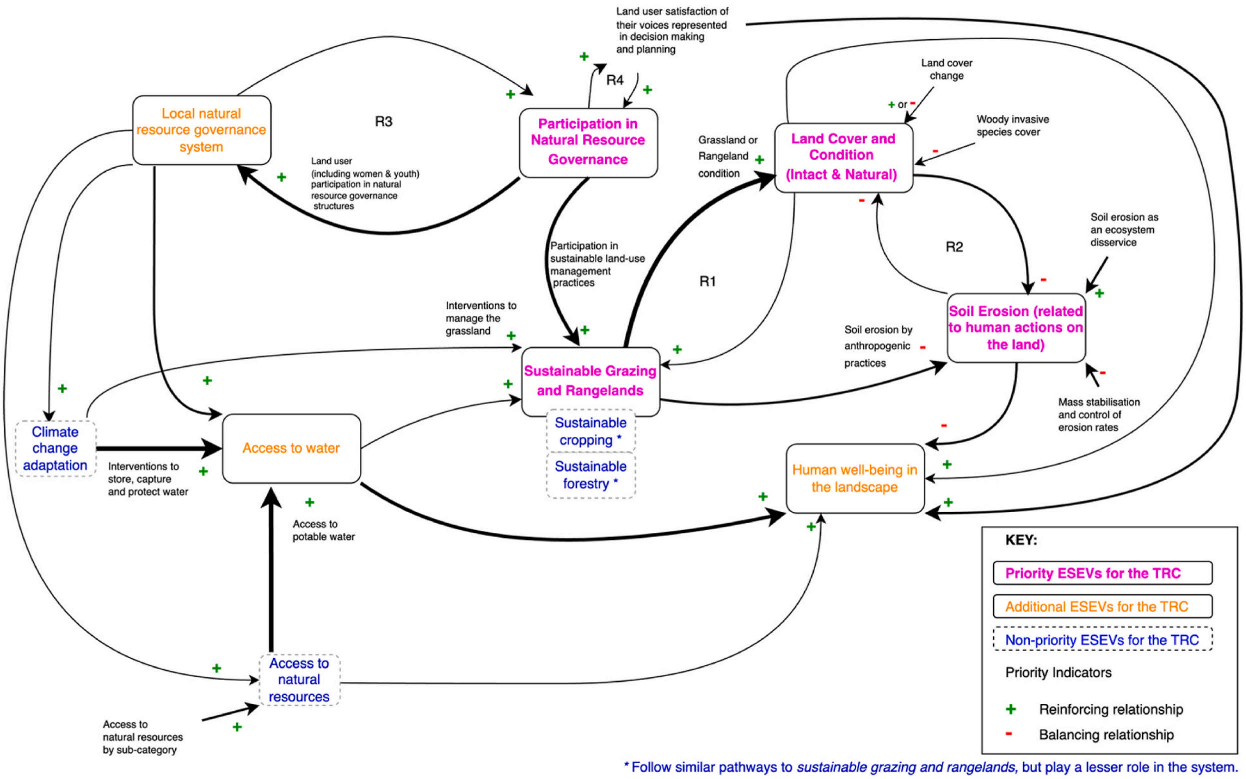

Fig. 5. Systems diagram showing the relationships between priority Essential Social-ecological System Variables (ESEVs), non-priority ESEVs and additional ESEVs that emerged from a transdisciplinary social learning process in the Tsitsa River Catchment (TRC). The green '+' signs on the arrows show relations where a change in the cause creates a change in the effect in the same direction, and the red '–' signs on the arrows show inverse relations, where a change in the cause creates a change in the effect in the opposite direction. Arrow thickness is indicative of the strength/importance of certain connections in driving the social-ecological dynamics of the TRC system, with the weakest links being the thinnest lines and the strongest links being the thickest lines. The diagram numerically identifies reinforcing loops 'R1'- 'R4'.

research, as well as the additional ESEVs later identified, versus the peripheral connections of the four non-priority ESEVs. The strong connectivity shows a close relationship between the sustainability of the landscape and the well-being of the communities.

4.2. Essential social-ecological system variables for sustainable livelihoods and restoration at catchment scale

Returning to the spatial part of the definition, the ESEVs proposed were applied at catchment scale, looking for changes that could be detected over the project period (annual to decadal scale). Monitoring at this scale, often utilized in integrated water resource management (Katusiime and Schütt, 2020; Savenije, 2002), focuses on the relations between land, water, and communities within the catchment. Results inform natural resource management decisions by local stakeholders and institutions. The fact that much of the EV work, including work on integrative EVs has been EO based (for example, Mccallum et al., 2020), may be a consequence of working at larger (regional or global) scales. Although EO remains as a data source, working at a catchment scale allowed for the incorporation of more varied sources of data to enable a more integrated social-ecological perspective. Employing a case study approach at this scale facilitated the identification of existing local institutions suitable for monitoring relevant, context-specific, social-ecological indicators. For instance, assessing participation and progress towards achieving the targets of grazing associations allows for the monitoring of relevant social-ecological relations in action (see 3.2.2). Monitoring through local institutions could also offer insights into the capacity of the local governance system (3.3.2) and inter-institutional relationships. Moreover, ESEV monitoring at the catchment scale could enable local institutions to utilize outcomes for adaptive natural resource management (Kingsford and Biggs, 2012).

Monitoring must align with indicator operational processes and long-term impacts, while also considering project objectives and timeframe. Monitoring is most pertinent for processes in which significant changes can be discerned primarily within the project's duration. Indicators in this study should be monitored at annual to decadal timeframes. Some indicators, such as mass and erosion rate regulation (3.2.1), were considered unsuitable due to mismatched timeframes.

The ESEV process could be tailored to address challenges in other river catchments. Although the ESEVs in this paper were developed for the TRC, many variables are applicable to other South African catchments with similar dynamics, such as Maqobeni, Tugela, and Olifants.

4.3. Areas of difficulty for social-ecological monitoring

Scale is a common area of difficulty for SES monitoring (Cumming et al., 2006; Maciejewski et al., 2015). The transdisciplinary team confronted challenges navigating the mismatches between the scales of ecological, social and institutional processes and monitoring (Itzkin et al., 2022). There was a mismatch between the scale of monitoring data using different methods. While EO collect broad scale data, observation methods such as transect walks and surveys collect more localized data which are not readily inferable to the catchment scale. While an ESEV approach does not explicitly address scale mismatches, by focusing on a significantly reduced set of data, it emphasizes key areas where the alignment of scale should be included in the approaches.

Difficulties in operationalizing certain ESEVs and indicators were identified. The ESEV, 'soil erosion (related to human actions on the land)' was highly prioritized, and while the associated indicators were also prioritized by the transdisciplinary team, upon further inspection with subject experts the indicators focusing on the anthropogenic contribution to erosion were found to be difficult to operationalize (see 3.2.1). Working across disciplines and in praxis brings varied perspectives but may lack the skills or knowledge to assess all selection criteria. Engaging subject experts is crucial for assessing feasibility. In the case of 'grazing and rangeland sustainability,' the overall ESEV was prioritized, but most related indicators were non-priority (see 3.2.3). This may be related to community reluctance to share sensitive data related to indicators such as G6 (income from sustainable livestock livelihoods), G7 (agricultural product sales rates), and G9 (livestock ownership patterns), making them difficult to operationalize.

4.4. Essential social-ecological system variables to make systems research simpler and more practical without losing the complexity

This study sought to simplify complex SES research outcomes without sacrificing their complexity. A participatory approach for ESEVs guided by both systems thinking and relational thinking, with a specific focus on practical application advances the realm of integrated SES monitoring. By adhering to the principles of requisite simplicity (Stirzaker et al., 2010), the proposed ESEV approach could assist in navigating complexities more effectively and efficiently, to find the simplest routes to understand the fundamental relational drivers of a system's dynamics.

5. Conclusion

This work has contributed to the understanding of social-ecological research in a rural catchment in southern Africa, where residents derive livelihoods from natural resources, and which is challenged by high levels of land degradation, a complex governance environment, and potential climate change impacts. By combining a transdisciplinary, participatory, systems approach, and a relational approach, a set of integrated Essential SES Variables was developed, which had not been done before. The ESEVs, including 'soil erosion related to human actions on the land,' 'participation in natural resource governance,' 'grazing and rangeland sustainability,' and 'land cover and condition,' hold the potential to inform integrated planning and management strategies at the catchment scale. In a world marked by complex development issues, the ESEVs pave the way for an integrative, adaptive, and contextually grounded approach to SES monitoring. This methodology is applicable to various SES landscapes.

The conceptual framing and methodology advanced in this study extend the realm of knowledge by offering a potent approach that underscores the importance of connectivity, context, and scale, contributing to simpler SES monitoring. The relational focus of this approach helps to overcome the dichotomies and dualisms in traditional SES monitoring frameworks, which reproduce separations between humans and nature. In conclusion, this study marks a significant step towards the advancement of SES monitoring by providing a rigorous framework of integrated ESEVs, reinforcing the importance of context, relational understanding, and adaptability in characterizing the dynamics of these complex systems.

CRediT authorship contribution statement

Adela Itzkin: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mary Scholes:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Kaera Coetzer:** Writing – review & editing, Supervision, Conceptualization. **Jai Kumar Clifford-Holmes:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2024.101106.

Data availability

The data collected by the authors of this study are available on request from the corresponding author. Data are not publicly available due to the need to comply with the ethics clearance certificate

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