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Decision Support Indicators (DSIs) and their role in hydrological planning

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ABSTRACT

Decision Support Indicators (DSIs) are metrics designed to inform local and regional stakeholders about the characteristics of a predicted (or ongoing) event to facilitate decision-making. In this paper, the DSI concept was developed to clarify the different aims of different kinds of indicators by naming them, and a framework was developed to describe and support the usage of such DSIs. The framework includes three kinds of DSI: *hydroclimatic DSIs* which are easy to calculate but hard to understand by non-experts; *impact-based DSIs* which are often difficult to calculate but easy to understand by non-experts; and *event-based DSIs*, which compare a current or projected state to a locally well-known historical event, where hydroclimatic and impact-based DSIs are currently mainly used. Tables and figures were developed to support the DSI development in collaboration with stakeholders. To develop and test the framework, seven case studies, representing different hydrological pressures on three continents (South America, Asia, and Europe), were carried out. The case studies span several temporal and spatial scales (hours-decades; 70–6,000 km^2) as well as hydrological pressures (pluvial and riverine floods, drought, and water scarcity), representing different climate zones. Based on stakeholder workshops, DSIs were developed for these cases, which are used as examples of the conceptual framework. The adaptability of the DSI framework to this wide range of cases shows that the framework and related concepts are useful in many contexts.

1. Background and objectives

Weather and climate extreme events frequently affect populations around the world. This is well documented by the monthly Global Climate Reports from the National Oceanic and Atmospheric Administration (NOAA) (NCEI, 2023). In recent years, several examples of extreme events such as storms, floods, droughts, and heatwaves, have been observed in many highly populated areas of the world. Such events expose that anticipation and preparedness for extreme events are insufficient (Kreibich et al., 2022). Moreover, future climate scenarios indicate increased frequency and intensity of extreme events. Despite major knowledge advances in climate natural variability, future projections, impact studies, services and adaptation, and research related to the occurrence of natural hazards, the use of this knowledge in societal planning is still limited. Klein and Juhola (2014) identify five "bottlenecks" for the use of research knowledge in climate adaptation decisions: 1) scientists' use of theoretical concepts that do not meet stakeholders' reality, 2) uncertainties in predictions of climate impacts, 3) the difference in the geographic scale of climate data and stakeholder needs, 4) the need to manage natural climate variability, and 5) that

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climate adaptation is just one of several factors that stakeholders need to consider. This means that stakeholder perspectives need to be considered on the use and relevance of available climate information, as well as the broader decision-making context in which adaptation decisions are to be made.

Different kinds of indicators are used for decision support in a wide range of disciplines, like transport planning (Marsden and Snell, 2009), remediation of polluted sites (Cappuyns, 2016), and descriptions of environmental state and policy implementation (EEA, 1999). Climate Impact Indicators (CIIs) are conventional model-based metrics used in hydrological modelling and impact assessment (Merks et al., 2020). As the term suggests, CIIs are most explicitly used in climate change studies, but the same (or similar) metrics are used in shorter-term forecasting. For the EU, the European Environment Agency (EEA) has developed a framework for physical, biological, and chemical indicators that reflects the state of the environment and monitors the progress made regarding policy targets (EEA, 1999). The so-called DPSIR framework, which is based on the pressure, state and response framework developed by the Organisation for Economic Co-operation and Development (OECD), connects *Driving forces* (social and economic developments), *Pressure* (e.g., pollution), *State* (e.g., biodiversity, water quality), *Impact* (e.g., on public health or ecosystems), and *Response* (intervention to mitigate problem) (Eurostat, 2014). This framework for environmental indicators is widely used both in policy follow-up and by researchers (Svarstad et al., 2008; Bell, 2012; Guo et al., 2016; Chandrakumar and Mclaren, 2018). The DPSIR framework has however been criticised for being a narrowly formulated, engineering device (Bell, 2012) and in the field of ecology, it has been criticised for not being neutral to different views on biodiversity (Svarstad et al., 2008).

This paper aims to develop the *Decision Support Indicator* (DSI) concept, to present a framework for DSIs related to the hydrological pressures of floods and droughts, and to exemplify the usage of such indicators. The DSIs are aimed at decision support pertinent to different climate zones, time horizons, spatial domains, hydrological pressures, and societal sectors. Regarding warning, forecasting, physical planning, and climate change adaptation, the need for proper communication of uncertainties related to the DSIs is important. The intention is to formulate indicators that are more tailored to decision-makers than the conventional indicators reviewed above, without the need for extensive data on the impact on society, ecology, and the economy.

2. Methods and study areas

This study is centred around seven case studies representing different hydrological pressures on three continents (South America, Asia, and Europe, see Fig. 1). Hydrological pressure, or *hydropressure*, is defined as the processes by which a hydrological system causes pressure on society. Four hydropressures are the focus of this study.

- *Water shortage* is the lack of water for water supply, irrigation, and electricity production.
- *Drought* is the lack of water in the environment, as well as agriculture and forestry, causing reduced plant- and crop growth.
- *Riverine flooding* is flooding along a river due to long-lasting rainfall and/or extensive snowmelt.
- *Pluvial flooding* is localised flooding due to intensive rainfall, exceeding the local infiltration and drainage capacity.

2.1. Indicator development

Indicators were developed based on stakeholder needs per case study as described by Beldring et al. (2020). The stakeholder process was mainly performed by stakeholder workshops locally organised by the case study leaders which have identified specific knowledge needs within the stakeholder groups. The results were the basis for developing a set of indicators that could be quantified using meteorological and hydrological observations and model results. Stakeholders represented several sectors of the society at local, regional, river basin and national levels responsible for legislation, environmental issues, urban planning, sewerage, water supply, infrastructure, protection against natural hazards and diseases, hydropower production, agriculture, and forestry.

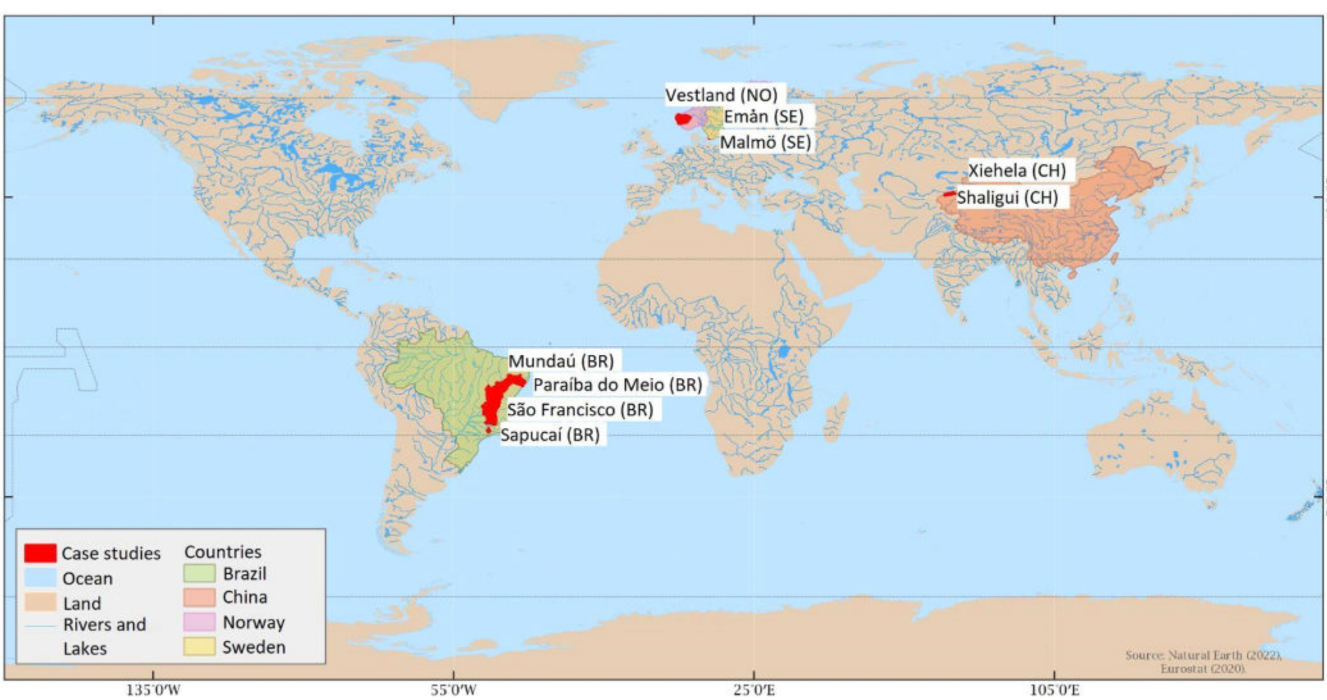

Fig. 1. Location of basins for the case studies used for the development of the Decision Support Indicator framework. Note that some basins belong to the same case study.

The stakeholder groups in the single case studies were compiled by the case study leaders and the size of the stakeholder group varies between 3 and more than 20.

Before the workshops, a questionnaire with nine open questions was jointly developed by all case study leaders to coordinate the stakeholder process in the different case studies. The questionnaire was focused on identifying the most relevant hydrological pressures in the respective regions from the stakeholders' perspective and identifying critical obstacles for coping with these pressures in terms of missing (or insufficient) knowledge, tools, and institutions. The questionnaire was kept generic to fit all case studies; however, the case study leaders could adjust and amend it as long as the general structure was preserved. In many case studies, a semi-structured questionnaire was developed from the common template which contained both open-format and closed-format questions.

Results from workshops and questionnaires were discussed subsequently, by researchers in a series of meetings where case-specific challenges and communication with stakeholders were discussed, and indicators were proposed. Based on discussions, stakeholders' needs and characteristics, it became clear that indicators based on statistics or hydrological/hydraulic characteristics would not fulfil the objective of reaching all stakeholders with an understandable message. Therefore, the concept of *Decision Support Indicator (DSI)* and a framework for DSI were developed, which is presented in this paper. First, after this section, the case studies used to develop the framework are presented. In Section 3, which is the core section, the DSI framework and the concept connected to it are presented in detail. In Section 4, decision-support communication is discussed, in Section 5 examples of DSIs from the chosen cases are described, and, finally, in Section 6, some concluding remarks are given.

2.2. Case studies

The case studies span several different temporal and spatial scales (hours–decades; 70–640,000 km^2) and hydropressures (Fig. 2), representing different climate zones, including tropical, semi-arid, monsoon, cold mountain, dry climate, mild temperate, oceanic temperate, and alpine tundra. In the following, the hydropressures in each case study are briefly described.

2.2.1. São Francisco (BR)

The São Francisco River in Brazil, with a length of 2830 km, originates in the Serra da Canastra Mountain range, in the state of Minas Gerais, and meets the Atlantic Ocean between the states of Sergipe and Alagoas, in northeastern Brazil. It is known as the "river of national integration" since it crosses five Brazilian states with different climate conditions (Freitas et al., 2022). According to the Köppen climate classification, the southern of the basin predominates by Aw climate (warm and humid tropical, with dry winters); in the middle, Aw and BShw (semiarid) prevail, and in the northeast of the basin, As (warm and humid tropical, with rainy winters) (CBHSF, 2016). Water transport to the semi-arid region of Brazil is one of the São Francisco main services (ANA, 2015; CODEVASF, 2015) but water availability is severely affected by the mechanism of climate variability in the region that many times has led to droughts (Coelho et al., 2016; Freitas et al., 2022). The socioeconomic impact of droughts in the region is extensively reported in the literature (Marengo et al., 2011; Coelho et al., 2016) and they impact different sectors. For instance, the expansion of irrigated agriculture throughout the basin over the last decades, associated with the worst drought on record, between 2012 and 2018, led to the occurrence of several conflicts over the use of water in this period. Therefore, the stakeholders are mainly concerned with the availability of water resources and the impacts of drought, especially on agriculture and hydropower generation.

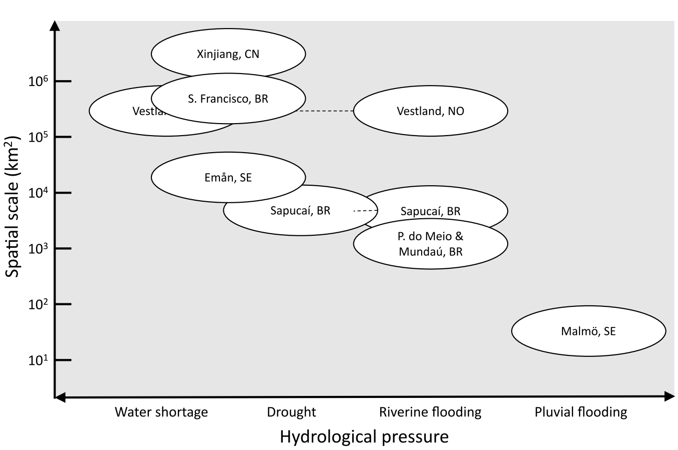

Fig. 2. Hydropressure and spatial scale for the seven case studies. Xinjiang, S. Francisco, and Emån are facing both water shortage and drought and are therefore located between them to save space. Vestland is facing both water shortage and riverine flooding. Sapucaí is facing both drought and riverine flooding.

2.2.2. Sapucaí (BR)

The Sapucaí River (248 km long) is located in the southeastern region of Brazil, primarily within the state of Minas Gerais. This river originates in the Mantiqueira Mountain range, in the state of São Paulo, at an altitude of 1620 m, and flows into the Furnas Lake in Minas Gerais, at 780 m. The climate in the region is characterised by monsoon (Ferreira and Reboita, 2022), in which most of the total precipitation is concentrated during austral summer. This region is affected by daily precipitation extremes, which lead to floods, but it is also affected by droughts. The city of Itajubá, in southern Minas Gerais, has a long history of floods, with the first records in the late 19th century (Barbosa et al., 2015). The last two major floods occurred in 1991 and 2000 (Reboita et al., 2017), and during the latter about 70% of the urban area was flooded. After this event, some measures were taken to dredge and enlarge the river channel within the urban area to improve the capacity. Since then, only a few small overflows have occurred. In parallel, studies were carried out to estimate flood magnitudes in terms of return period and a monitoring network was implemented.

For the Sapucaí River basin, only recently drought has become a problem (Coelho et al., 2016). Since 2013 the flows recorded in the basin are below the historical average, and in 2021, the lowest ever flows were recorded (in 91 years of records).

2.2.3. Paraíba do Meio and Mundaú (BR)

The Paraíba do Meio and Mundaú in Brazil are two neighbouring river basins that together have an area of 7,300 km^2. They both have shallow soils with a rapid response to rainfall events. The climate is governed by a wet season and a climate gradient from the littoral towards the continental zones. The average annual precipitation in the upper part of the basins is about 800 mm and in the lower parts about 2,000 mm. The dry season is from September and March, and the wet season is from April to August, during which more than 70% of the total annual precipitation falls. The rainiest months are May–July. During the rainy season, frequent extreme rainfall events may occur, causing flash floods. Therefore, the stakeholders are mainly concerned with riverine floods and their socio-economic impacts on inundated areas along rivers and urban planning.

2.2.4. Xinjiang (CH)

The Xinjiang Uyghur Autonomous Region in China is the area on Earth that is the most remote from any ocean. Conflicts between irrigation and drinking water supply are a key issue in the area. Due to increased consumption of water for domestic and agriculture use, the runoff has decreased and even disappeared in the lower reaches of some rivers (Shi et al., 2022), making the hydropressure even more intense than before. Therefore, the stakeholders are mainly concerned with the availability of water resources and the impacts of drought with additional attention on the agriculture activities within the local area as well as the downstream area. In this study, two headwater catchments in the Tarim River Basin are in focus for this case: Shaliguilanke and Xiehela.

2.2.5. Vestland (NO)

For the Vestland region in Western Norway, with an area of 33,781 km^2, severe and prolonged water deficit periods have caused major problems in recent years, with substantial impacts on water supply and hydropower production. Low lake and groundwater levels threatened the water supply in the winter of 2009/2010, and electricity prices rose to unprecedented high levels due to low reservoir storage. Water deficit also occurred in 2018, 2006, 2002/2003, and 1995/1996. Many watersheds in this region have been developed for hydropower production, the dominating supply of electrical energy in Norway.

The Vestland region also frequently experiences rainfall and snowmelt events that produce flooding and landslides, causing considerable threats to human health, local communities, and infrastructure. Recent events occurred in 2014 and 2018. Heavy rainfall events and fluvial flooding are projected to become more frequent in a warmer climate. The stakeholders are mainly concerned with design flood estimation for hydropower dams, roads and railways, other areas along rivers, and urban planning.

2.2.6. Malmö (SE)

The City of Malmö is located in southern Sweden and has a temperate climate. Malmö has a history of using nature-based solutions for stormwater management, where the Eco-City neighbourhood (Augustenborg) and green roof research conducted there are famous (Månsson and Persson, 2021; Emilsson and Sörensen, 2021). In 2014 (31^{st} of August), a severe flood event occurred in Malmö and the efficiency of these systems was verified (Sörensen and Emilsson, 2019). The 2014 flood event affected areas all over Malmö and was worse than all previous events in modern times (Sörensen and Mobini, 2017; Kreibich et al., 2022), with high costs for people, companies, the public water utility company, and insurance companies (Mobini et al., 2020). Since this event, stormwater management in Malmö has been more concerned with flood risk reduction and climate adaptation. For instance, a municipal water strategist was appointed. The 2014 event has also been the focus of research on adaptation measures in Malmö as well as in Sweden overall, as it was one of the events that raised interest in pluvial flooding in Sweden (Berndtsson et al., 2019; Olsson et al., 2021; Sörensen et al., 2016).

2.2.7. Emån (SE)

The Southern Sweden case study focuses on drought and water scarcity in the Emån River basin, with an area of 4470 km^2 and a temperate climate. The region experienced an early summer drought in 2016–2017, leading to scarcity and water use restrictions, followed by a severe drought and water scarcity also in 2018. Like in Sapucaí (BR), water scarcity is unusual for the region and consequently, preparedness was low. Another issue is scarce data on water use, e.g., if all irrigation permits were to be fully implemented, the river could dry out (Stensen et al., 2019). As a response to the 2016 event, in Emån as well as in other basins, in 2017 the Swedish Meteorological and Hydrological Institute began issuing advisories of water scarcity. Envisaged impacts are to facilitate better decision-making related to water scarcity and drought by providing tailored information and tools. The issuing of risk for water shortage does not *per se* set limitations of water use. Those limitations are defined in the permits for water operations and by regional authorities. There have been concerns that irrigation bans might not always be adhered to. In 2022, the Swedish Coastguard therefore intended to monitor this with airplanes (Montelius, 2022).

3. Decision Support Indicators (DSIs)

In both present and future climates, the hydrological pressure on shorter (hours, days, weeks) as well as longer (season, decade, century) timespan is generally assessed by hydrological modelling, where the hydrological model is forced with either forecasts or projections of the meteorological drivers (mainly temperature and precipitation) (Arheimer and Lindström, 2015). This pressure is then assessed together with other pressures to determine the total environmental pressure on e.g., water resources, agriculture, forestry, safety, public health, energy production, or infrastructure. Frequently, economic, or social impacts of floods and droughts are considered, e.g., the costs of damage to infrastructure or crop failure, or threats to human health.

In general, Decision Support Indicators (DSIs) are *metrics designed to inform local and regional stakeholders on the characteristics of a predicted or ongoing event to facilitate decision-making.* Although indicators based on the direct output from hydrological modelling, here regarded as *hydroclimatic DSIs*, may provide useful information, there are currently several limitations concerning the uptake by stakeholders and decision-makers. One key aspect is the difference in scale between stakeholders' needs and the type of results generated (Olsson et al., 2016). The typical situation is that the results are too coarse in space and/or time and that local variability is not reproduced. Another aspect is the lack of information regarding consequences related to a certain state of the DSI. This problem can be solved by adding another analysis of consequences to society, ecology, or economy to the hydrological model output, which will give what is here regarded as *impact-based DSIs*, but these require extensive data that are often not available.

In the following, we develop the DSI framework, including new terminology and useful figures to support collaboration on DSI development with stakeholders. As a part of this work, we develop *event-based DSIs* that relate the severity and/or likelihood of an event to the previous experience of the local population and stakeholders, which we compare to *hydroclimatic* and *impact-based* DSIs (e.g., Samaniego et al., 2019, Ekström et al., 2018). The idea of the event-based DSIs is to *relate forecasts, projections, and planning to (recent) historical extreme events.* This is achieved by first defining historical events that serve as a baseline, and subsequently expressing any future or ongoing event relative to this historical baseline. The historical event should be a specific extreme historical case that would still be vivid in the mind of the population in general and stakeholders in particular. Event-based DSIs aim to ensure the understanding of non-hydrologists and laypersons composing a large part of the users.

While classical metrics and statistics (the hydroclimatic DSIs) often are difficult for stakeholders to relate to, it is hoped that using historical events as a benchmark will greatly improve the end users' ability to understand the implications for society, ecology, or economy and to identify the need for action concerning a predicted or expected future event. Expressing hydropressures in relation to the observations made during a historical, well-known extreme event may help users to understand/estimate/assess impacts, based on experiences from the actual event. It has also been noted that (recent) historical disasters and extreme events are seldom used as much as they could be for gaining improved understanding and confidence in the models.

Fig. 3 is the first component of the DSI framework and shows the hierarchical relation between the three main DSIs, including the kind of information a DSI conveys, ranging from hydrological aspects to including one or several societal impacts. The target group they aim to help, the transferability of the results, and the role of models are also shown.

While hydroclimatic indicators are mainly targeting hydrologists, impact-based indicators are targeting well-informed practitioners, as they present specific information with immediate relation to decisions taken. Event-based DSIs are an intermediate step between hydroclimatic and impact-based DSIs when it comes to model complexity and input data needed. They can meet some of the requirements for local

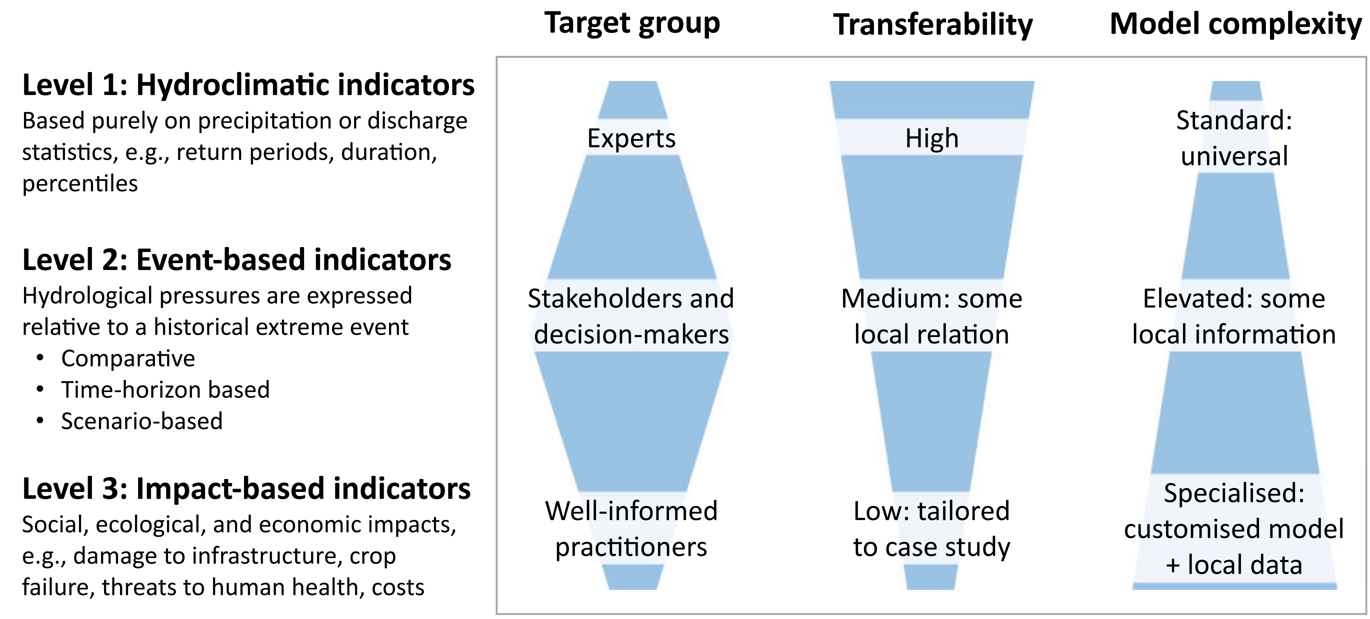

Fig. 3. Hierarchy of DSI and their target group, transferability, and the role of global models related to different DSI levels.

stakeholders, even if the information given, i.e., with reference to a historical reference event, is not as specific and detailed as impact-based DSIs. In some cases, when the impact-based DSIs are more difficult to interpret, the event-based indicators can even be more tailor-made towards decision-makers.

The hydroclimatic DSIs are more or less universal, meaning that the indicators can be transferred from one case to another, while the impact-based DSIs are tailored and cannot be transferred. As the event-based indicators are based on a historical reference that should be well-known to the stakeholders, they cannot be transferred to any other case. Still, transfers to other sites nearby, where the historical reference is known, are possible.

Concerning modelling, hydroclimatic indicators may be provided by models covering different domains, even the entire globe, although the precision is conceivably higher the smaller the model domain. For event-based indicators, global models may be able to provide a signal (e.g., an early warning), but generally more location-specific models are required to obtain a reliable simulation of certain events. Finally, impact-based indicators will always need a location-specific model as the detailed data needed are not readily available on global or continental scales.

Another component of the DSI framework is the three dimensions for DSIs that have been identified (Fig. 4), i.e., 1) the hydrological pressure they relate to, 2) the planning horizon they are used for, and 3) the level of information they contain.

The planning horizon can be divided into early warnings and physical planning. *Early warnings* are used close in time to prepare for a possible upcoming event or to inform about an ongoing event. Depending on the hydropressure, the warning sometimes needs to cover as long as seasonal projections, to be relevant. The time scale of a warning reflects the spatial scale of the hydropressure and the response time in the catchment. While water scarcity due to low groundwater availability relates to the slow process of groundwater recharge, pluvial flooding is governed by the short time scale of convective rainfall and the response time in the drainage system. *Physical planning* includes both short-term planning of the built environment, infrastructure, environmental protection, and risk management for the coming years as well as long-term planning of buildings and infrastructure that will remain for a long time, where climate change is essential and/or climate change adaptation and protection of biodiversity is the main goal. Longer time horizons of the DSI, like when they are used for physical planning, require slower driving processes to be considered.

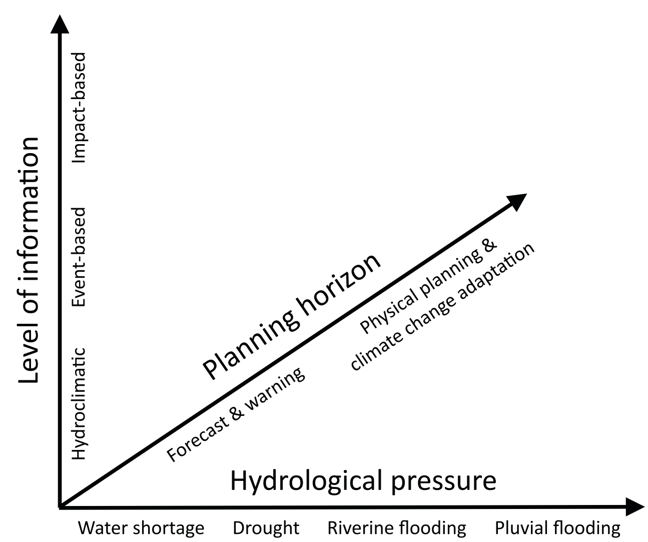

Fig. 4. Three dimensions relevant for DSIs.

The drivers behind hydrological pressure, like glacier retreat, land-use changes, and climate change, do also influence the choice of DSI. While this study is mainly concerned with pluvial flooding, riverine flooding, water shortage and drought, the DSI framework can also approach other hydrological pressures.

3.1. DSI categories

In the following, the three main types of DSIs, i.e., hydroclimatic, impact-based, and event-based, are discussed in greater detail. As mentioned before, probably the most frequently used DSIs are the hydrological description of the level of threat from a certain hydropressure, here called *hydroclimatic DSIs*. These DSIs regard current and/or projected water levels or discharge at a certain point in the river (typically by a station) (Kim et al., 2022; de Faria et al., 2022), projected inundation area (Li et al., 2021; Darabi et al., 2021), measured and/or projected water level in wells, etc., or return period/probability for the same parameters. These DSIs are valuable to hydrologists who are trained in interpreting them but tend to be less intelligible to professionals from other fields and even less to decision-makers and the general public.

Impact-based DSIs include parameters related to effects on e.g., economy, health, infrastructure, ecology, or water provision and can improve risk communication with stakeholders with little or no hydrological training and to get a direct understanding of expected consequences. These DSIs can answer questions related to the *social, ecological,* and *economic impacts* of hydropressure and aim to give the extent of the probable damage in an extreme flood or drought event or the usefulness of certain measures. Examples of such indicators are:

- How many residents will be affected by this flood event?
- What will be the reduction in production at the soy plantations in this drought?
- What is the probability of an outbreak of water-related diseases during the next season?
- What is the economic benefit of this climate change adaptation measure?

As the impacts are not directly available from hydrological models, these DSIs require additional analysis or modelling with additional datasets. The lack of such data is a common problem.

If the link between the hydrological pressure and the impacts is unknown or difficult to assess, *event-based DSIs* can be used. By referring to a historic, well-known event, the potential impacts of a new, possibly upcoming event are more easily understood by stakeholders. Therefore, stakeholders can be more involved in the decision-making, having a better understanding of the severity of the situation. The event-based DSIs are especially valuable, as they require little additional data or analyses in comparison with impact-based indicators. Event-based DSIs have been used in different situations, by different institutes, and for different purposes. However, to the best of our knowledge, this is the first time they have been formulated as generalised and coherent categories/concepts to use as a basis for project implementation. Three generalised event-based DSI categories are outlined below, and an example is given in Table 1. The table combines the two components presented graphically in Figs. 3 and 4. An empty template (Appendix A) could be used to develop and discuss potential DSIs with stakeholders.

3.1.1. Event-based DSIs: comparative

The idea is to characterise an event in magnitude/duration/extent *relative to a historic event*. For warnings, a comparative DSI could for example be formulated as “Based on the current forecast, the event will affect twice the area compared to the 2014 flood event” or “Based on the current forecast, the event will last twice as long as the 2018 drought event”. For planning a comparative DSI could be “An extreme rainfall like 2014 will occur on average every 10 years by the end of the century”. These DSIs are straightforward to understand for all involved stakeholders, as they directly relate the (coming, ongoing or future expected) event to the historic event.

3.1.2. Event-based DSIs: time horizon-based

The idea is to provide an estimate of the *time left either until a critical historical threshold is reached or the normal state is again reached*, which is a very tangible and intuitive type of information. This information can generally be extracted from existing forecasts and projections but may often not be explicitly provided/communicated. Two examples are: "When will we reach a flood level similar to the 2014 event with the current forecast?", and "With experience from the 2021 event, when will it end?" (“It” could be the flood, the discharge above the warning level, etc.). The latter example (when will it end) has been requested by stakeholders in the project.

3.1.3. Event-based DSIs: scenario-based

The idea is to compute *“what-if” scenarios* to provide the user with some knowledge beforehand about the possible/probable consequences of different weather/climate evolutions and/or decisions taken. These DSIs could be “What if 30 mm more rainfall comes, will we then reach the flood levels of 2014?” or “Given the current medium-range forecast, how much water can we withdraw for irrigation without risking falling below low flow levels of the 2018 drought?”

Scenarios may be combined with time horizons, i.e., that a critical threshold for discharge, soil water, or groundwater is reached at a certain time. Two examples that are of interest for drought could be ”After how many more days without rainfall will water stress for the vegetation be similar to the situation in 2018?” or ”After how many more days without rainfall will groundwater levels fall below those during the drought in 2018?”

Pressure on natural systems from both land use and climate change impacts, as well as changes in management strategies, are relevant for DSIs. Scenario-based DSIs can potentially combine weather/climate scenarios with other relevant scenarios, e.g., land use or population.

3.2. Decision-making process

The DSI development must be adjusted to the involved decision-makers and the purpose of the DSIs. While decisions on action often are made by professionals in Scandinavia (incl. Sweden and Norway), politicians are more involved in Brazil. Many of these politicians do not have technical knowledge or training in the area and they rarely remain in the same positions within the public administrations for many years which reflects in inconsistencies in their decisions. In China, these kinds of decisions are often made by a combination of professionals and politicians. The professional background of the decision-maker will affect how the situation is best communicated. During a hazard, when decisions are made by the local or higher-level authorities based on warning systems, the indicators must be communicated with a clear message explaining what to do, when and by whom under such circumstances. In addition, the target audience must be well known by the organisation providing the warning, in order to ensure proper communication of the warning.

Table 1
Example of DSIs for each type and planning horizon. The example regards drought.

			Planning horizon	
			Forecast and warning	**Physical planning and adaptation**
DSI type	**Hydroclimatic**		The forecasted event will affect an area of 20,000 km^2.	By the end of the century, the average drought duration will increase by 20%.
	Event-based	**Comparative**	The forecasted event will affect twice the area of the 2018 drought.	By the end of the century, an event like the 2018 drought will occur on average every 31 years.
		Time-horizon based	Based on the current forecast, the low flow levels of the 2018 drought will be reached in 15 days.	The 2018 drought will have a return period of 50 years by the 2060 s.
		Scenario-based	After 10 more days without precipitation, we will reach the low flow levels of the 2018 drought.	Under a high-emission pathway, the 2018 drought will have a return period of 25 years by the end of the century.
	Impact-based		The forecasted event will lead to crop losses of 30%.	By the end of the century, drought events will cause crop losses of, on average, 10% per year.

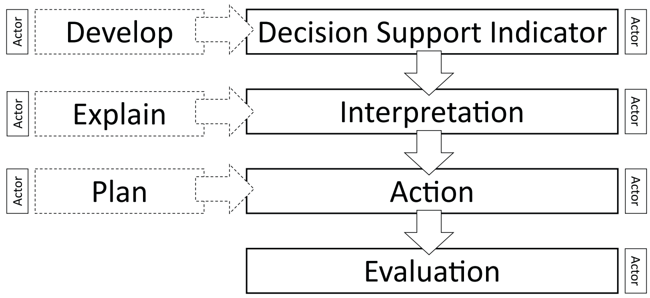

Fig. 5. The role of Decision Support Indicators in decision-making, where the left-hand side represents actions by developers and the right-hand side represents actions by decision-makers.

Several different types of decisions are taken by the stakeholders (Fig. 5), including decisions regarding the development of DSIs, interpretation of them, actions taken to limit the harm of a hydropressure, and evaluation after an action has been taken. In Fig. 5, the role of DSIs in the decision-making process is presented. As can be seen, there is a direct link between what the developers do (left-hand side), and the actions taken by decision-makers (right-hand side). There, the stakeholders must be involved in the whole development and implementation process. First of all, the DSIs are developed. With a proper explanation from the developer, the stakeholder will interpret the DSI either during an ongoing event or for planning purposes and, if needed, take action. The action will follow a developed plan. Note that such a plan probably is developed by a different professional than the one who developed the DSI and the explanation. Finally, after the action plan is implemented, the stakeholder will evaluate the decisions made as well as the suitability of the DSIs available. For long-term planning, the action plan would probably be called a development or risk reduction plan.

4. Communicating extremes

Extreme events like drought and floods are highly connected to large uncertainties, mainly as the predictions reach completely outside collected observations or are based on only a few similarly extreme observations (Sörensen and Mobini, 2017). For DSIs, including future predictions and scenarios, the large uncertainty can be difficult to interpret or consider in physical planning and decisions. Indicators related to climate change have generally been designed and produced by natural scientists, for large geographic areas, and with a top-down approach where ensembles of climate projections are used to produce ensembles of climate impacts. This becomes a huge mass of results spanning different time horizons, emission scenarios, models, scales, and hydrometeorological variables. It is, therefore, a challenge for non-experts to use the information in a meaningful way and the risk of misuse is obvious.

Forecasting the near future is often considered an initial condition problem, while climate change modelling is more of a boundary condition problem (e.g., Meehl et al., 2009). Observations, internal model states and the choice of model and model parametrization are important for the success of both weather and hydrological models, while the emission scenarios and process parametrization are critical to represent future climate. Uncertainty in a climate change aspect is hence reflected by different scenarios describing narratives of expected socio-economic behaviour in the future. Communication of uncertainty to the public and the stakeholders might therefore be different depending on the forecast horizon. Morss et al. (2008) found that for weather forecasts people mostly interpreted probability into forecasts and understood that forecasts were more uncertain further ahead. They found that there was a fair understanding of forecast uncertainty, and they could relate to a certain forecast bias. Understanding the user expectations and their references are important in the communication of forecast uncertainty. Experience of past forecasts will influence how the stakeholder will act upon a new forecast.

IPCC has chosen to show a number of scenarios that all depend on future emissions (IPCC, 2021). These scenarios represent uncertainty but do also communicate a clear message to decision-makers and the global public: Depending on how we act, global warming will be higher or lower and this will influence our future climate.

To represent uncertainty in the physical aspects of climate change Shepherd et al. (2018) suggests using 'storylines' defined as "physically self-consistent unfolding of past events, or of plausible future events or pathways" and the following four reasons is why:

I. Storylines can improve risk awareness. Events rather than probabilities improve individual risk perception and risk response. It is easier for people to relate to events or similar previous experiences.
II. Storylines can strengthen decision-making. Compound risk and appropriate stress tests can be developed by working backward from a particular vulnerability, threshold, or decision point by combining climate change information with relevant factors affecting local impact.
III. Storylines can provide a physical basis for partitioning uncertainty. By allowing for alternative credible regional models to be used in a conditioned manner it is possible to explore the impact of relevant physical processes. 'How much worse would the impact be if…?'
IV. Storylines can be used to explore the boundaries of plausibility. Using models as tools to test and explore theories regarding process interaction is useful when the quantitative aspect of the Global Circulation Model (GCM) does not represent the local impact for specific processes. For example, to capture or represent changes in intense precipitation, a high resolution convective permitting model is needed representing deep convection and not only parametrize such processes in the GCM.

According to Intrieri et al. (2020), the type and objectives of communication should be different if it is being done under normal conditions or if it is done during (or on the verge of) an extreme event. Under normal conditions, it is necessary to inform the vulnerable population about the risks they are exposed to, about safe behaviour, about the dynamics of natural processes and about the functioning of the alert system. These actions increase the population's perception of extreme events. Availability of information and advance training of the population will facilitate crisis communication, should events occur, as the intended message with the DSIs will be correctly understood. On the other hand, at the verge of an extreme event, the focus is on warning messages and how they are conveyed. The key elements to be defined for a warning message are who is the sender of the message, what is the content and how it is sent (Intrieri et al., 2020). Crisis communication should be institutional, efficient, rapid, reliable and it should use multiple communication channels. It should preferentially focus on the use of infographics, which are generally more immediate and effective than plain text. According to Kuller et al. (2021) the inadequacy of responses to flood warnings has two common causes: low individual risk perception and a lack of self-efficacy. To increase the risk perception, the communication needs to be specific and is recommended to use brief warnings, to be more effective. It is not a simple task, because a warning message is a balancing between being short enough for quick comprehension and covering all essential information (Kuller et al., 2021). A common problem in flood risk communication is that scientists do not use the proper language to engage with decision makers (Wood and Miller, 2021). And finally, the communication must be transparent about what is known, what remains unknown and what is uncertain and must be consistent (Kuller et al., 2021).

Flood risks can be characterised as low probability/high consequence risks that are often underestimated by individuals. Perception of the risk of an extreme event is influenced by factors such as gender, age, economic condition, educational level, cultural aspects, time spent in the place and the history of exposure to events (Rufat and Botzen, 2022). In general, people who had been directly affected by flood were not satisfied with early warning (Mahdavian et al., 2020). The main problem is that warnings underestimate the severity of the situation and should come in time. Therefore, we can say that early flood forecasting is still not enough. At the same time, the perception of severity or risk can change before and after experiencing flood events. In such cases, referring to a historical event may help receivers to better interpolate content of warnings.

4.1. Examples of and experiences from DSI communication in the case studies

The risks of floods and extreme weather conditions must be effectively communicated to the general public since the awareness of those risks can motivate preparation for the event (Haer et al., 2016) potentially, helping to reduce loss of lives (Doocy et al., 2013). In this context, the communication of DSIs related to floods in Sapucaí River Basin with municipal stakeholders and the general population has improved over the last few years due to the partnership between the city administration and the university. The Federal University of Itajubá (UNIFEI) provides daily operational weather and hydrological forecasts through an openly available website (CEPreMG, 2023) to local civil defence. UNIFEI's professors in meteorology and hydrology answer the community's questions through radio shows and TV interviews. With these actions it is possible to notice the keen interest of the population about information regarding river floods and extreme weather events. During the extreme rainfall events of December 2021 and January 2022, UNIFEI's Meteorology Website registered more than 47,000 visits. Questions from the general public, especially during radio shows, help scientists and stakeholders to improve how to communicate and highlight the need for changes in the way of presenting technical information. When communicating with the public it is always important to be succinct and avoid technical expressions. The same applies to the communication with the stakeholders.

The Norwegian Meteorological Institute and the Norwegian Water Resources and Energy Directorate forecast meteorological and hydrological conditions in Norway with a lead time of a few weeks and issue warnings about events that may cause threats to society through media and a website (NVE et al., 2023). The Norwegian media, decision makers and the general public are well informed about forecasts of hydroclimatic hazards. References to previous events are common when a situation with hydroclimatic pressures arises. Information about previous flood events is available through a website (NVE, 2023). The impacts of climate change on hydroclimatic conditions including extreme events are projected by several institutes and communicated by the Norwegian Centre for Climate Services through a website (NCCS, 2023). Although decision makers, and to some extent the media, have established an understanding of the vulnerability of society to climate change during the present century, these projections are less well understood by the public, and comparisons between projections of future conditions and previous extreme events are frequently not available.

In Sweden, as written above, advisories of water scarcity started to be issued in 2017. An advisory is less severe than a warning and aims at putting public attention to a situation that may develop into a state where impacts may be encountered. The advisories are based on discharge forecasts one month ahead and the probability of remaining below the 95th percentile. The resulting risk of surface water scarcity is combined with the current state of groundwater levels and communicated as country level maps with counties at risk highlighted. In the associated text, the affected rivers (or river reaches) are specifically mentioned. The advisories are updated once a week and are published on the SMHI website (SMHI, 2023). Additionally, the so-called 'hydrologist on duty' is available for questions from users, media or the public. Although there is no formal procedure for relating the current state to historical events, the drought in 2018 is occasionally used in analysis and communication.

Often it is assumed that a precise prediction is more valuable to stakeholders than an imprecise one. However, if the preciseness comes with a longer calculation time, the quick-and-dirty prediction might be more appreciated. This has been pointed out by hydropower industries in Sweden when they use flow predictions from SMHI.

5. Examples of DSI development and usage in the case studies

In the following sections, hydroclimatic, event-based, and impact-based DSIs developed or discussed in this study according to the presented framework are presented (Table 2).

5.1. Hydroclimatic DSIs

For the São Francisco River basin, a set of hydroclimatic indicators are planned for drought: 1) Hydrological classification based on flow duration; 2) Percentage of flow in relation to the minimum flow (Q7,10); 3) Percentage of useful volume in reservoirs. The Standard Precipitation Index (SPI; McKee et al., 1993), which can indicate meteorological or hydrological droughts, is applied to the São Francisco River basin (Freitas et al., 2022).

In the Emån river basin, drought advisories are based on discharge forecasts one month ahead and the probability of weekly averaged flow remaining below Q95. Attempts were made in this project to improve seasonal forecasts of the number of days below Q95 based on daily flow and using different conditioners for analogue years. However, it was difficult to achieve improvements given the sensitivity of this indicator towards short-term hydropower regulations (Elenius and Lindström, 2022) and water use, for which there is insufficient information. Weekly averages, as in the advisories, might have simplified the developments. Climate indicators are available online from SMHI and include the change in the number of days that have flow lower than the mean annual low flow in the period 1971–2000.

Both in Vestland and Xinjiang, several hydroclimatic DSIs are used for planning and climate change adaptation to drought, like average drought duration ($F(Q) < 0.2$), average deficit volume, drought duration, percentage change in threshold value corresponding to $F(Q) < 0.2$ of seasonal inflow, change in annual discharge, and return period of the most severe event in terms of deficit volume and duration in the historical period by the end of the century under different emission pathways.

For Malmö, a flood hazard map for 100-year rainfall is used in municipal planning. The 100-year return period is recommended for pluvial flood management in Sweden by several authorities and organisations. The 100-year return period is also used for goals, e.g., that "at latest in the year 2045, pluvial flood planning should have led to that all of Malmö can handle a 100-year event with minimal harm to property and people, and with a minimum of disturbance as a consequence" (own translation) (City of Malmö, 2017).

For Paraíba do Meio and Mundaú, two hydroclimatic DSIs for both floods and droughts are used: hydrological reports with alerts based on

Table 2
Types of DSIs developed in this project or currently used by stakeholders and therefore discussed below.

	Drought and/or water shortage	Riverine and pluvial flooding
Hydroclimatic	Brazil, Sweden, Norway, China	China (riverine), Brazil (riverine), Norway (riverine), Sweden (riverine & pluvial)
Event-based	Brazil, Sweden, Norway	Brazil (riverine), Norway (riverine), Sweden (pluvial)
Impact-based	Sweden, Norway	Brazil (riverine), Sweden (pluvial)

water level for droughts and floods and how the climate changes could change the basin precipitation dynamics towards flood and droughts occurrence.

In Vestland, a set of hydroclimatic DSIs are used to inform stakeholders about climate change effects: future return period of today's 100-yr and 50-yr flood, change in magnitude, the shift in the mean day of flood occurrence, and the shift in flood-producing mechanisms. The latter is the source of water responsible for generating flood events, whether rain, snowmelt, glacier ice melt, or a combination of these. Norwegian legislation has requirements regarding return periods of floods in different cases. Long-term planning of hydropower production applies a similar procedure, with an estimation of droughts as a critical hydrological pressure (Wong et al., 2011). Hydrological modelling and flood frequency analysis are used for estimating hydroclimatic DSIs (Filipova et al., 2019; Hegdahl et al., 2020; Lawrence, 2020).

In the Sapucaí basin, it was decided to continue using the hydroclimatic DSI that alerts high water levels of the Sapucaí River, where flood levels are mapped in the city of Itajubá, as it is a simple, real-time measure that is easy to understand by the population (Fig. 6). When the water level is high, the message can easily be communicated through social media (Fig. 7). The use of flows associated with return times was discarded since the concept of these flows is not understood even by those responsible for Civil Defence. One event-based indicator, namely the water level during the extreme flood event in 2000, is marked on the hydroclimatic DSI (Fig. 6).

Fig. 7. Infographic to inform the population about the level of the river, released through social media during the rainy season in January 2022. Source: Municipality of Itajubá.

5.2. Event-based DSIs

In this study, event-based comparative DSIs were developed for the São Francisco Basin, which relates the magnitude of an ongoing event to historic events known by the stakeholders and compares reservoir volume with the same month of last year in percentage. This information is important as the conditions are easily remembered by stakeholders.

The same DSIs as for the São Francisco River basin will also be used for Sapucaí, except DSIs on reservoirs. An example of how the flow level is illustrated in Sapucaí River is shown in Fig. 8. It consists of a graph with the hydrological classification constructed from the durations of the flow time series. In addition, minimum reference flows can be entered for water abstraction. Flow forecasts for the period ahead are shown. Currently, this graph is generated monthly to evaluate the hydrological conditions of the previous month. A version with flow forecasts is being prepared. For floods, an event-based, comparative DSI has been developed for Sapucaí River: water level difference in relation to the 2000 event.

For Vestland, two event-based DSIs that relate to a severe event in the recent historical period were developed for drought in this study: 1) future periods are compared to the most severe, recent historical event in terms of e.g., deficit volume, and 2) return period of the most severe, recent historical event is estimated for the end of the century under different emission pathways.

In Malmö, event-based indicators have been used in planning for several years. After the severe flood event in Copenhagen in 2011, this event was used for comparative indicators of pluvial flood risk in Malmö. For instance, a scenario-based flood hazard map was developed with a precipitation time series from central Copenhagen in 2011 (Hernebring et al., 2015), which shows that transfer of event-based

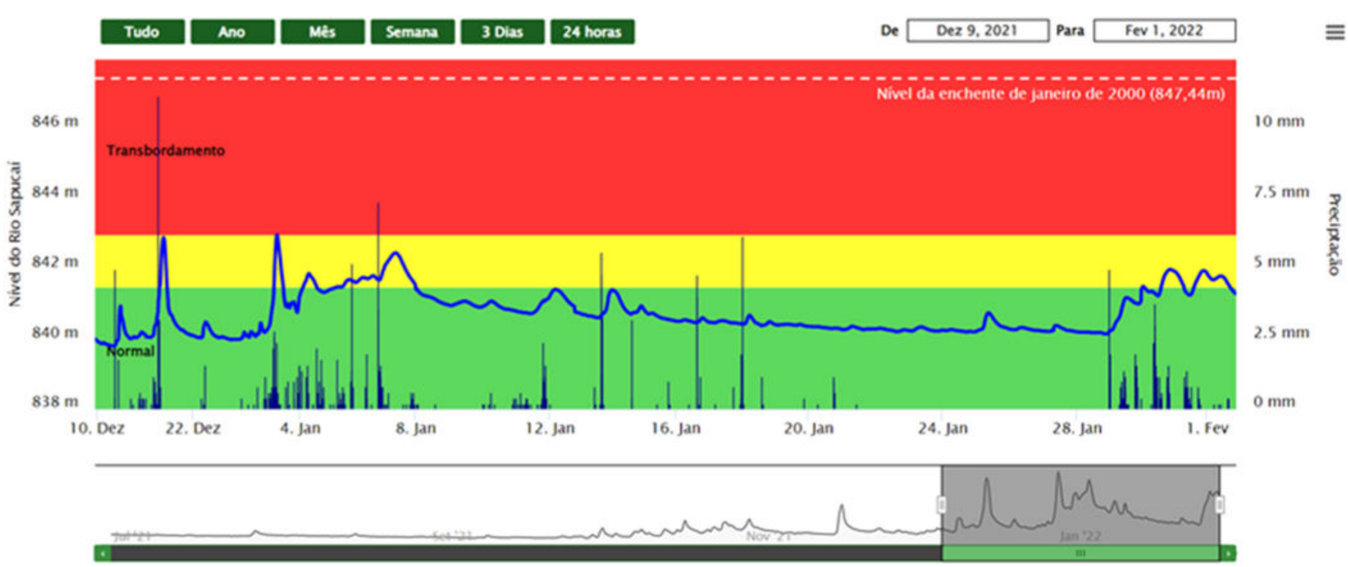

Fig. 6. Indication of the water level and the alert state of the Sapucaí River, 2021/12/09–2022/02/01 (available at: meteorologia.unifei.edu.br/hidrologia). Monitoring is carried out at a reference hydrological station at the beginning of the urban stretch of the Sapucaí River. The historical flood event of 2000 is marked with a dashed line.

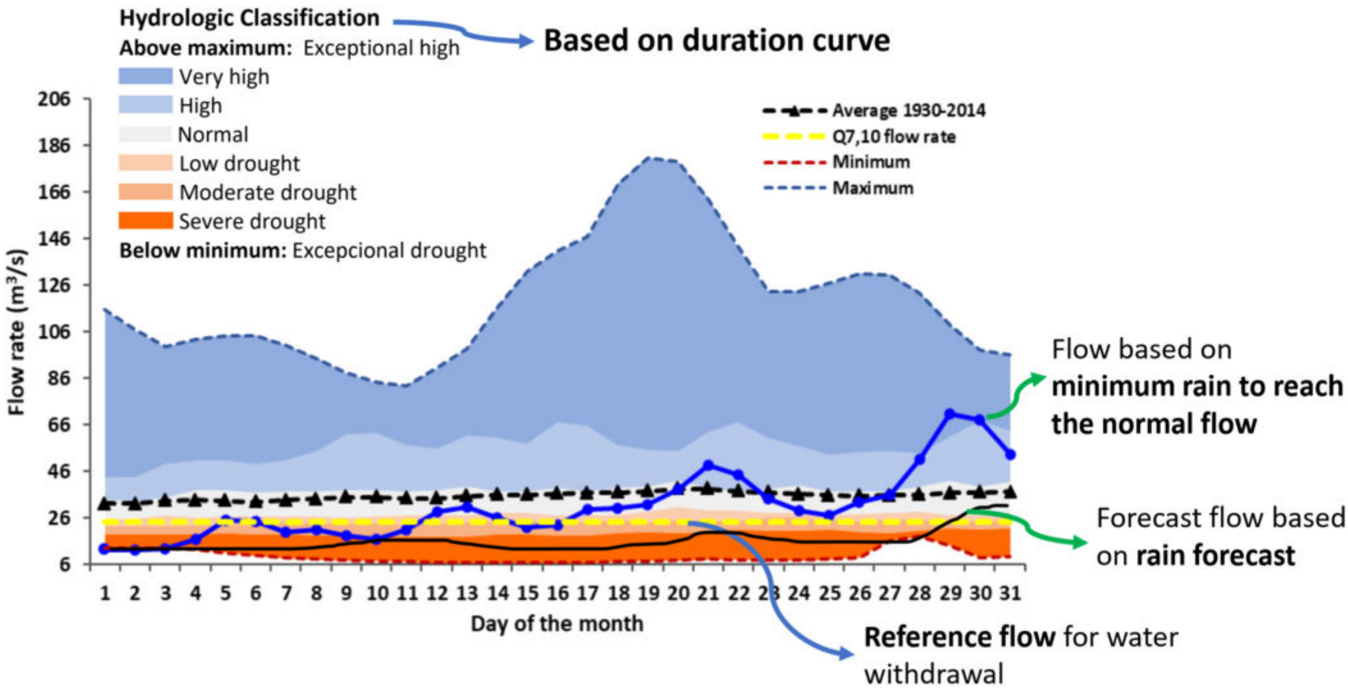

Fig. 8. Graph with indicators for droughts in the Sapucaí River basin, October 2021. In the background, historical measurements are shown with an indication of severe drought (red) to very high flow (blue). Flow based on the minimum rainfall required to reach normal flow is shown (blue line), as well as a forecast based on available rain forecast (black line). In addition, the average flow (1930–2014) (dashed, black line) and Q7,10 are shown (yellow, dashed line).

indicators is possible between nearby places. After the 2014 event in Malmö, Copenhagen 2011 was used for comparison of rainfall intensity to illustrate the severity of the Malmö 2014 event (Hernebring et al., 2015).

For Paraiba do Meio and Mundaú, several event-based DSIs for planning and adaptation have been developed in this study: magnitude, duration, and extent of flooding relative to a historical event (comparative), number of hours or days with heavy rainfall to reach a water level similar to a historical event (scenario-based), and probability of a historical event in the future vs return period of a historical event in the future (comparative).

For Vestland, one event-based DSI has been developed for riverine flooding. It looks at the direction of change (decrease/increase) in the return period for a given event size (reference event). Will the selected event occur more frequently or less frequently in the future?

For Emån, the extremely low flow in October 2016 was used as a reference when comparing with other years in a scenario-based evaluation of flow development with no rain. Time-horizon-based indicators have also been used in communication of a later low-flow situation in 2022 with stakeholders, to explore the time until flow increases again. This was performed by studying the amount of rain that was required to reach normal flow in a previous year with a similar drought and then evaluating the time to produce this amount of rain in previous years.

5.3. Impact-based DSIs

For Emån, but including an evaluation based on data for all of Sweden, we have tried estimating the impacts of low flows on trout populations for their use as an impact-based DSI (Elenius, n.d.). It was found that Swedish data do not currently support the use of trout as indicator species for low flow. The absence of any clear impact of low flow on trout was estimated to be due to insufficient spatial resolution of flow data and time resolution of trout data, in combination with data quality and, not the least, the migratory behaviour of trout.

For Vestland, the reduction in potential hydropower production caused by drought events, present vs. future, is used as an impact-based indicator. This indicator informs on the effect of drought years, expressed as percentage reduction in annual potential hydropower production compared to present-day mean annual potential hydropower production as a sum over the entire region.

The City of Malmö has developed a pluvial flood risk map, where the risk is calculated as maximum 100 years flood depth multiplied by an assessment of vital societal functions (resolution 200×200m). The map identifies the most vulnerable areas and serves as a basis for a flood action plan (City of Malmö, 2017).

For Paraiba do Meio and Mundaú, two impact-based indicators have been developed. The first indicator focuses on the urban population and includes the number of people at flooding risk, the geographic extent of the impact, and the characteristics of the urban area that may influence the magnitude of the flooding event. The second indicator addresses the expected economic losses. This means that it seeks to quantify the financial impact that the event will have on the region, considering factors such as damage to property, infrastructure, local industries, loss of revenue and other affected economic aspects. These indicators are useful tools for evaluating and planning responses to anticipated events. They allow stakeholders to understand the magnitude of potential impacts, assess the risks involved and make informed decisions to mitigate damage, protect lives and reduce economic losses.

For the Sapucaí river basin, economic losses from the flood event in 2000 have been estimated. In Fig. 9a, the spatial extent of the 2000 flood is shown. From this area it is possible to estimate several indicators, such as the total affected population (Fig. 9b), affected urban infrastructure, affected public service buildings and other buildings, interrupted streets, economic damage, etc. Fig. 9d shows the impact-based DSI with estimated economic losses from the 2000 flood for a neighbourhood in the city (Fig. 9c). These estimates quantify the different costs related to the recovery of homes affected by the floods, such as cleaning, damage to structures, contents, and vehicle losses (Fig. 9d). By repeating these calculations for different levels of flooding, economic loss curves can be constructed (Fig. 9e), which can be used by the municipal government in planning and decision-making concerning flooding in the city.

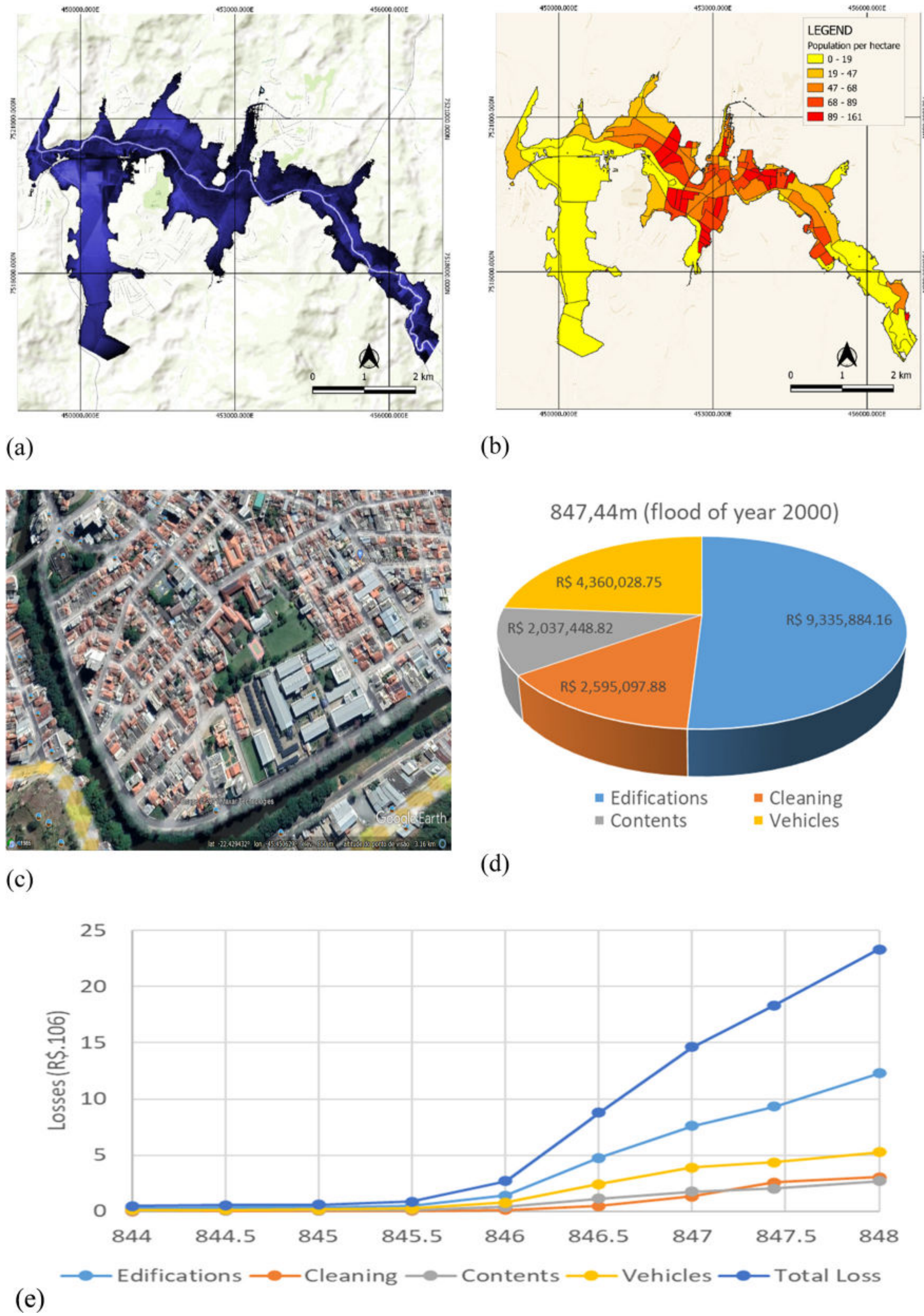

Fig. 9. Impact-based DSI has been constructed for the Itajubá urban area. Part a) shows the flood map of the Sapucaí River in the stretch within the urban area of Itajubá, for the year 2000 flood, b) shows the density of people residing within the flood area, c) shows a sample of urban occupation in the central region of the city, d) shows expected losses considering the flood of the year 2000, and e) shows expected losses for different flood water levels.

6. Concluding remarks

In this study, the Decision-Support Indicator (DSI) framework has been developed based on discussions with stakeholders for seven case areas around the globe where hydrological extremes such as drought and flooding are problematic. A DSI is an indicator used in decision-making. Various indicators are used already; here we underline their role by terming them DSIs and introduce three DSI categories: *hydroclimatic DSIs* which are easy to calculate but hard to understand by non-experts and *impact-based DSIs* which are often difficult to calculate but easy to understand by non-experts. In between these two categories, we propose a new category, *event-based DSIs*, which compares a current or projected state to a locally well-known historical event. That means we do not have to estimate the impacts, but non-experts still get an idea about the possible impacts due to their experience of the historical event.

In comparison to the DPSIR framework, which has been developed since the 1970 s and is used by organisations like the European Environmental Agency, OECD, and UNEP for environmental assessment (Svarstad et al., 2008), the DSI framework is narrower and more directed towards hydrologic extremes. In DPSIR, society shapes *Drivers* that could put *Pressure* on the environment. The environment will then have a certain *State* which will *Impact* society, which might lead to a *Response* from society. In the DSI framework, using DPSIR terminology, a hydropressure is an extreme hydrological state of the environment. These extreme events can cause stress on either society or nature or both. While DPSIR does not explicitly talk about natural values, the DSI framework includes nature in its own right and emphasises the importance of nature conservation and resilient ecosystems, besides safe and well-functioning societies. In the DPSIR framework, a state in the environment might be harmful or not to society, but the DSI framework emphasises the problem of hydropressures that directly harm the natural environment and/or society.

One hydroclimatic DSI that has not been proposed in any of the case studies, but discussed during the framework development, is a DSI reflecting the *predictability* of the flow in a catchment. Especially for the operation of for instance hydropower and water supply, the predictability is of great importance and stakeholders in this study have mentioned that lower predictability is a concern related to climate change. Three possible hydroclimatic DSIs were suggested: 1) deviation from normal timing, 2) changes in the number of events in the future, and 3) average uncertainty in forecasts. This DSI could be further developed in future studies.

Another useful DSI category that has been discussed is impact-based DSIs which are a combination of several factors. For instance, CEMADEN in Brazil combines the probability of an extreme event with the local vulnerability. A risk index can be developed where hazard, exposure, and vulnerability are combined. SMHI in Sweden has also started to combine hazard and exposure in their current national impact-based warning system, e.g., by issuing flood warnings based on flood mapping. Situations that might severely affect society are graded higher in the warning system, compared to situations with less exposure.

Besides event-based DSIs developed in this work, other ways to make valuable DSIs that are easy to understand could be to develop impact-based DSIs with simple models, like regression models. They can then be used in combination with the other DSI categories: comparative, time-horizon-based, and scenario-based, and would probably require less data compared to other impact-based DSIs, but with the price of a higher uncertainty compared to impact-based DSIs.

CRediT authorship contribution statement

Michelle S Reboita: Conceptualization, Investigation, Writing – review & editing. **Benedito C Silva:** Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Nívea A D Pons:** Conceptualization, Investigation, Writing – review & editing. **Stephanie Eisner:** Conceptualization, Methodology, Visualization, Writing – review & editing, Investigation. **Daniela R T Riondet-Costa:** Conceptualization, Investigation, Writing – review & editing. **Johanna Lykke Sörensen:** Conceptualization, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Stein Beldring:** Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Project administration. **Cintia Bertacchi Uvo:** Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing, Funding acquisition. **Jonas Olsson:** Conceptualization, Investigation, Project administration, Writing – original draft, Writing – review & editing, Methodology, Funding acquisition. **Maria Elenius:** Investigation, Writing – original draft, Writing – review & editing, Conceptualization. **Vanessa S B Carvalho:** Investigation, Visualization, Writing – review & editing, Conceptualization. **Carlos Ruberto Fragoso Jr:** Investigation, Writing – review & editing, Writing – original draft, Methodology, Project administration. **Trine Jahr Hegdahl:** Investigation, Writing – original draft, Writing – review & editing, Conceptualization. **Anna Hansen:** Investigation, Writing – original draft, Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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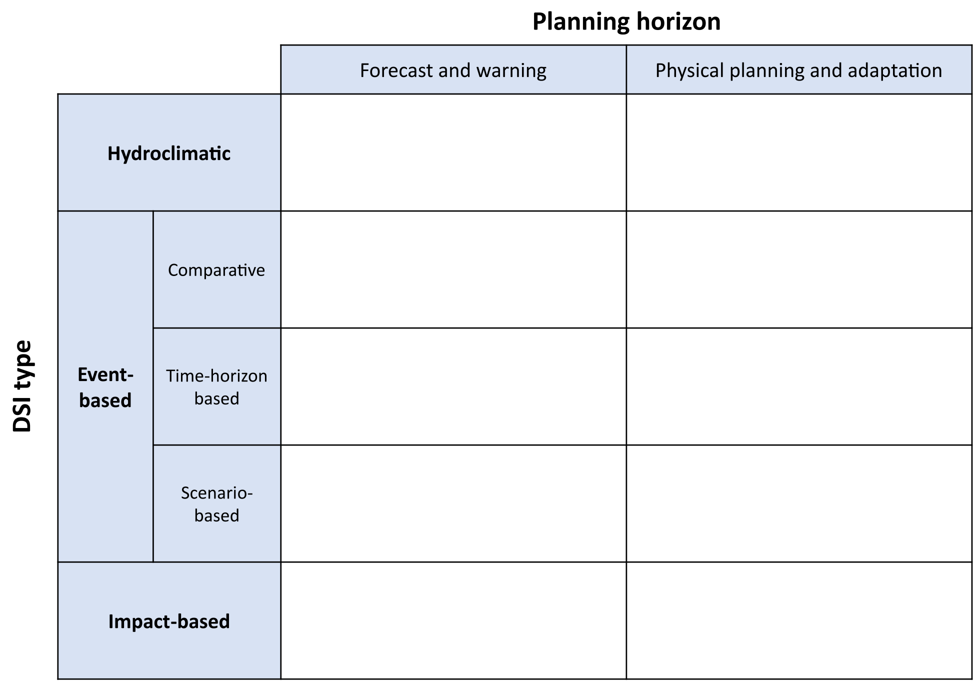
Appendix A

Template to be used for developing and discussing potential DSIs with stakeholders.



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