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Review of literature on decision support systems for natural hazard risk reduction: Current status and future research directions

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A B S T R A C T

Natural hazard risk is largely projected to increase in the future, placing growing responsibility on decision makers to proactively reduce risk. Consequently, decision support systems (DSSs) for natural hazard risk reduction (NHRR) are becoming increasingly important. In order to provide directions for future research in this growing area, a comprehensive classification system for the review of NHRR-DSSs is introduced, including scoping, problem formulation, the analysis framework, user and organisational interaction with the system, user engagement, monitoring and evaluation. A review of 101 papers based on this classification system indicates that most effort has been placed on identifying areas of risk and assessing economic consequences resulting from direct losses. However, less effort has been placed on testing risk-reduction options and considering future changes to risk. Furthermore, there was limited evidence within the reviewed papers on the success of DSSs in practice and whether stakeholders participated in DSS development and use.

Contents

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1. Introduction

Model-based Decision Support Systems (DSSs) are used extensively to support the management of our environment across the ecological, social and economic spheres. For example, DSSs have been developed for sustainable management of fisheries (Carrick and Ostendorf, 2007); farming and other agro-systems (Bazzani, 2005; De la Rosa et al., 2004; van Delden et al., 2010); the management of habitat and ecosystems (Booty et al., 2009; Wong et al., 2003); land development (Shi et al., 2012; van Delden and Hurkens, 2011); the delivery of utilities, such as water supply (Abramson et al., 2014) and community planning (Lieske, 2015; Papathanasiou and Kenward, 2014; Sahin and Mohamed, 2013); water resource management considering rivers, lakes, wetlands, reservoirs and their catchments (Berlekamp et al., 2007; Casini et al., 2015; Giupponi, 2007; Matthies et al., 2006; McIntyre and Wheater, 2004; Mysiak et al., 2005; Romañach et al., 2014; Soncini-Sessa et al., 2003; van Delden et al., 2007); and the management of contaminated sites (Marcomini et al., 2009). The benefit of applying model-based DSSs to decision problems, is that they can:

1. Support policy relevant questions (Geertman and Stillwell, 2003; Parker et al., 2002; van Delden et al., 2007);
2. Focus on long term and strategic issues (Geertman and Stillwell, 2003; van Delden et al., 2007);
3. Facilitate group interaction (Geertman and Stillwell, 2003; Newham et al., 2007);
4. Facilitate effective decision outcomes in complex, poorly-structured or wicked decision problems, which have many actors, factors and relations and are characterised by high or unknown uncertainties and conflicting interests amongst actors (McIntosh et al., 2007; Rittel and Webber, 1973);

5. Incorporate intuitive interfaces between end users and software (see for instance Volk et al., 2008; Volk et al., 2007);
6. Integrate interdisciplinary data and process knowledge (van Delden et al., 2007)
7. Operate on different temporal and spatial scales and resolutions, as appropriate (van Delden et al., 2007; Volk et al., 2010);
8. Adequately capture system dynamics, including feedback loops, such as those that occur between individual models (van Delden et al., 2008; van Delden et al., 2007);
9. Be built using flexible and modular software systems that can be efficiently maintained, extended and adapted to similar case studies (Argent, 2004).

The development and use of DSSs for natural hazard risk reduction (NHRR) is increasingly important, for several reasons. These include:

1. **Natural hazards are having a significant impact on communities and economies:** Natural hazards are causing significant losses, both in terms of lives lost and economic costs. According to the Impact Forecasting Database, the 10-year average cost of natural disasters is $255 billion per year (Daniell et al., 2016a, 2016b). Although these losses are a small portion — on average, slightly less than 0.3% of the US$79.4 trillion global GDP (mid-2015 CATDAT estimate, Daniell et al., 2016a; Daniell et al., 2016b), natural disasters are localised and have very severe impact on local economies and communities, and recovery usually takes a very long time. In addition, the potential costs from natural disasters are an order of magnitude greater than averages — losses from large, infrequent events which have not been experienced in recent years are extremely large. For example, a repeat of the 1923 Tokyo earthquake could cause over US$2.0 trillion in economic losses, over US$30 billion in insured losses, and over 40,000 deaths (See also Grossi et al., 2006). Considering the potential losses caused from natural hazards, DSSs help policy advisors, stakeholders and decision makers explore the options they have available in reducing the impact of these hazards on their communities.
2. **Losses due to natural disasters are expected to increase into the future**: There are two main factors for this increase: The first is climate change. The 5th IPCC assessment finds that storm surge, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, aridity, water scarcity, and air pollution hazard are increasing with climate change (IPCC, 2013, 2014a, b). The second is that populations and economies continue to grow, and are increasingly concentrated in urban areas, consequently increasing exposure and vulnerability (Bouwer, 2010; Changnon et al., 2000; Kunkel et al., 1999; Neumayer and Barthel, 2011). This is aggravated by cities often developing adjacent to rivers and oceans that form the backbones of navigation/transport systems (Glaeser and Kohlhase, 2004; McGranahan et al., 2007; Small and Nicholls, 2003), and populations often congregating around fertile basins formed through alluvial flood deposition or soils of volcanic provenance. In addition, as cities grow, supply of land to facilitate growth reduces, which results in human developments using land that is more vulnerable. DSSs can help explore how risk will change in the future, and what needs to be done contemporaneously to abate these risks.
3. **Risk reduction is broadly recognised as being more effective than response and recovery:** There is increasing evidence showing the benefit of pre-hazard risk-reduction (i.e. risk-reduction actions undertaken prior to a hazards event). For example, Rose et al. (2007) found that the overall benefit-cost ratio across nearly 5500 Federal Emergency Management Agency risk-reduction grants was about 4:1. The English Environment Agency tested funding strategies for maintaining existing, and investing in new, flood risk management assets across England and found that the optimal expenditure on mitigation was £25 billion over the next century with a benefit-cost ratio of about 5:1, when the costs and benefits for managing coastal, tidal and river flooding, and managing coastal erosion were considered (Environment Agency, 2014). Harper et al. (2013) investigated three risk-reduction projects in Australia for flooding, storm and bushfire risk, and found that benefit cost ratios were better than 1 and up to 9 where risk-reduction investments were made that target high-risk locations with appropriate combinations of structural and non-structural measures. Despite these benefits, risk reduction is broadly recognised to be lacking sufficient investment (Hennessy et al., 2014; Sadiq and Weible, 2010; Wood, 2004). DSSs can help make stronger cases for risk-reduction options through visualising their effects, testing their performance under different uncertainties and future scenarios, and providing a transparent and consistent analysis platform, as well as the quantitative evidence to support decision making.
4. **Risk reduction and residual risk affect communities and the natural environment in multiple ways, with complexity and uncertainty in causal processes driving hazard impacts**. Consequently, it is unwise to rely solely on experience when deciding upon mitigation plans, especially when considering large impacting, low frequency events (it has been shown that people who have not experienced large events tend to underestimate their likelihood, while people who have experienced large events overestimate their likelihood, for example, see Botzen et al., 2015). Instead, analytical approaches should be used within the planning process to remove human bias. However, there are significant difficulties in the analysis of risk-reduction options (for example, see Hennessy et al., 2014; IPCC, 2014b; Sadiq and Weible, 2010; Stein and Stein, 2014; Vaziri et al., 2010; Wood, 2004). Some of the contributing factors to this are the need to deal with deep uncertainty (Lempert and Collins, 2007; Lempert et al., 2003; Maier et al., 2016; Walker et al., 2013), long time frames, system non-stationarity, evaluating intangibles and characterising the trade-offs between different stakeholder values and expectations. Analysis also needs to consider a large range of risk-reduction measures that act in very different ways, requiring the integration of a diverse set of models. Risk-reduction options are implemented across many different departments and at many different levels of government and the private sector; thus, different decision criteria may need to be developed for decision makers across multiple organisations with different cultures and values. DSSs integrate numerous modelling components to take into account the complex causal processes and interactions that give rise to different types of hazard impacts, and therefore have capability to calculate a wide variety of decision indicators.

Given the impact of natural disasters and the fact that these impacts are likely to increase in the future, the likely benefits of risk reduction, and the difficulty of assessing the relative benefits of different risk-reduction options, it is timely to review progress that has been made in terms of the development of DSSs for natural hazard risk reduction and to identify future research directions. To achieve this, this review paper:

1. Proposes a systematic classification system for the review of NHRR DSSs, including all of the factors that have been found to be important for the uptake of DSSs in practice;

2. Surveys papers in peer reviewed international journals that have reported on the development or use of NHRR DSSs through the lens of the classification system in order to identify gaps in current research efforts in this area, as well as future research directions in relation to the various components that will improve the development and use of NHRR DSSs.

The remainder of this paper is organised as follows: the proposed classification system for the review of NHRR-DSSs is introduced in Section 2. Details of the papers included in the review and the process for their selection are given in Section 3, while the findings of the review are given in Section 4. Finally, a summary of the findings and an outline of future research directions are provided in Section 5.

2. Proposed classification system for the review of natural hazard risk-reduction decision support systems

The proposed classification system for the review of NHRR DSSs is shown in Fig. 1. This classification system was developed to not only cover the capabilities of DSS software alone, but has a focus on the broader development, implementation and use processes that a DSS is embedded within.

For the purposes of this classification, a NHRR DSS comprises software that provides value to analysts, decision makers and/or stakeholders during risk reduction planning processes, for example through the nine benefits listed in the Introduction. Although many NHRR DSSs include capability for calculating expected hazard, loss or risk, they do not necessarily need to, for they may provide visualisation or means of comparing different risk reduction options from exogenously calculated risk, for instance. In addition, they may be software that can be applied to a variety of different contexts across different organisations through to those that are specifically tailored to a particular decision context and user. Likewise, we do not consider a model that calculates risk to be necessarily a DSS if it does not provide value to risk reduction planning.

As mentioned above, a focus of this classification is the development and implementation processes that have been shown to be critical for actual use of a DSS. As pointed out by van Delden et al. (2011a), it is critical that development and implementation processes include both 'hard' and 'soft' factors so that they are effective in bridging the science-policy gap. Hard factors relate to "the selection and development of a model, model integration, model evaluation and the selection of the software platform" and soft factors relate to "linking scientific knowledge to information relevant to policy support," facilitating the "social learning of the different groups involved" and working through the "role of champions and the implementation of DSS in (policy) organisations".

Consequently, the proposed review framework covers all of the steps that have been identified as being important for the successful development and use of integrated models and DSSs (e.g. Hamilton et al., 2015; van Delden et al., 2011a), rather than the technical capabilities of DSS software alone, which have already been reviewed elsewhere (Daniell et al., 2014). As can be seen, the taxonomy is divided into six main components, four of which address the development of DSSs, while the other two are focussed on their use, monitoring and evaluation.

As mentioned above, the classification includes four components relating to the development of NHRR DSSs, and activity on each of these components has a rough chronological ordering. First, 'scoping' concerns the needs of users, taking into account the decision processes that are to be supported, and the information needed for this. Second, after the scope of the DSS has been formulated, the specific problems to be addressed need to be formulated, as shown in the 'problem formulation' component. Third, a 'modelling framework' then needs to be specified that analyses the effectiveness of risk-reduction options. Finally, modelling outputs need to be processed and presented within software to enable users to interact with the system in an intuitive and helpful way within decision making processes. This last process is included within the 'user and organisational interaction with the system' component.

After a DSS has been developed, it is deployed into an operational setting. The two components relating to this are 'Use and user engagement', and 'monitoring and evaluation'. It should be noted that although these components have been presented as representing DSS development as a waterfall process, in reality there is a need for iteration between components which, to a large extent, occurs due to end-user engagement as well as monitoring and evaluation during development cycles (van Delden et al., 2011a). Therefore, these last two categories are also ongoing throughout the development of a system.

As detailed in the following subsections, review categories are provided for each of the components in the classification system. The development of these categories was based on information from the literature, and refined and/or expanded to make it fit for purpose for surveying natural hazard DSSs. This enabled papers to be reviewed in a consistent and transparent manner, as was done in previous DSS reviews (Arnott and Pervan, 2008) and reviews published in other domains (e.g. Maier et al., 2010; Wu et al., 2014). The findings of this review enable a number of important questions, in relation to papers focussed on NHRR DSSs, to be answered within the discussion, such as:

- Where have DSSs been applied, for what purpose and at what level of management?
- What hazards have been considered and have they been considered in isolation or in an integrated manner?
- What natural hazard risk criteria have been used, and how have they been chosen, calculated and presented?
- Over what time horizon has risk-reduction planning taken place and how have uncertainty and dynamics in future conditions, particularly around demographics, land use, climate, and economics been addressed?
- How have the various elements of risk (i.e. hazard, exposure, vulnerability) been modelled?
- How successfully have DSSs been deployed, and are they used for their intended purpose in practice?

Further details on each of the components of the proposed classification system, as well as the review categories for each of these, are given in the following sub-sections.

2.1. Scoping

Scoping is vital in ensuring the efforts made in developing a DSS result in a product that has relevance in decision making processes. The categories that fall under the scoping component include the function and use of the DSS, the hazards considered in the DSS, the planning horizon and temporal resolution of the DSS, as well as the geographic extent and spatial resolution of the DSS. Further details on each of these components, in addition to the specific review categories for each of these, are given in the following subsections.

2.1.1. Function and use

Function and use captures the different purposes for which natural hazard risk-reduction DSSs can be developed. The subcategories used for function and use were adapted from Wallace and De Balogh (1985), and are broadly categorised into DSSs that

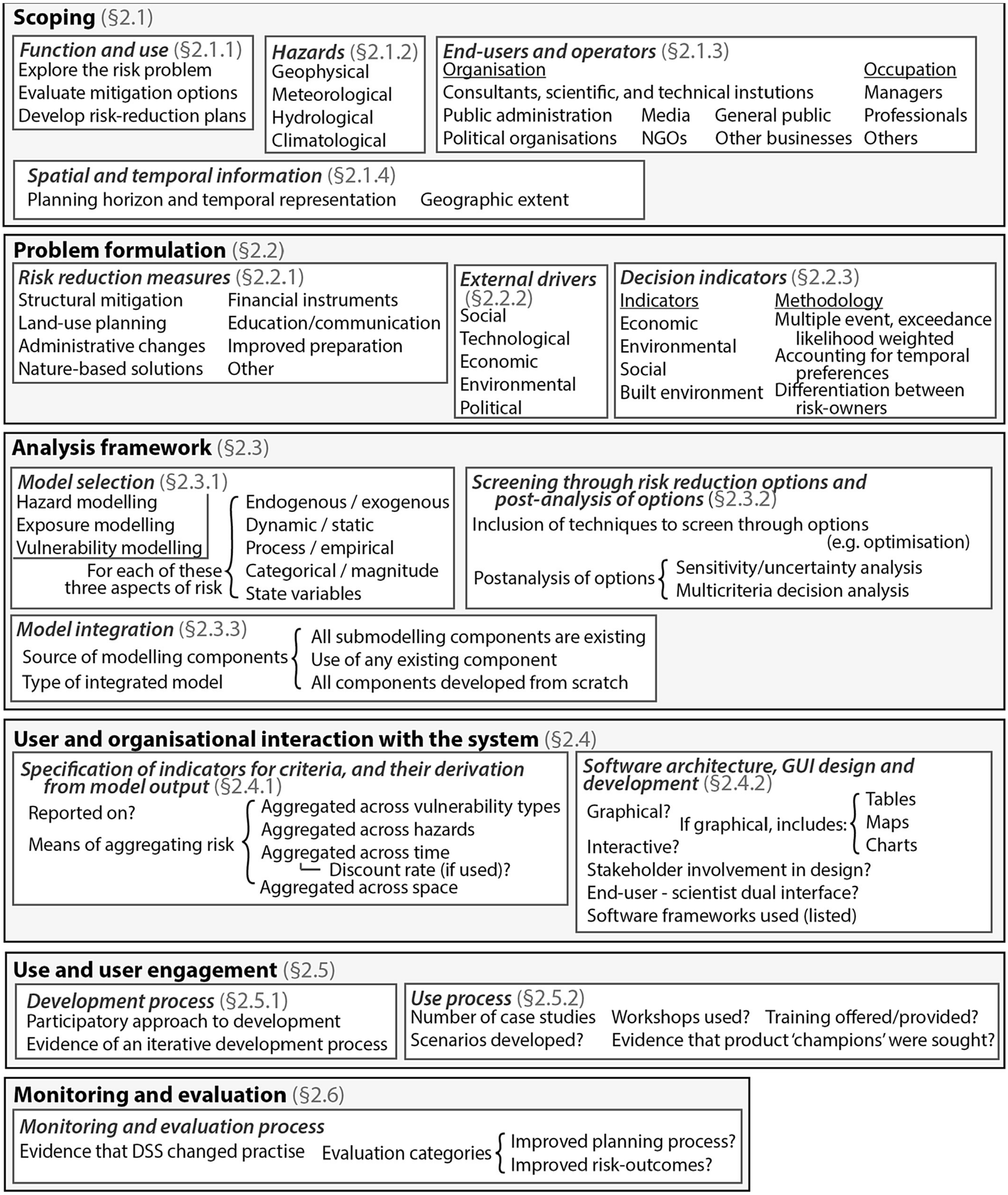

Fig. 1. Proposed classification system for the review of natural hazard risk-reduction decision support systems.

Fig. 2. Subcategories for function and use.

(1) explore the risk problem, (2) evaluate risk-reduction options and (3) make risk-reduction plans, as shown in Fig. 2.

2.1.2. Hazards

One or multiple natural hazards may be considered in a DSS. As part of the proposed classification system, the review categories for hazards include *physical* disasters that are quick onset, but excluding *extra-terrestrial* disasters (such as hazards caused by meteorites) as categorised by the DATA project of IRDR (Integrated Research on Disaster Risk, 2014), being:

- *Geophysical* hazards, including earthquakes, tsunamis, volcanic eruptions, and dry mass movements;
- *Meteorological* hazards, such as hail and storms (including cyclones, tornadoes, thunderstorms, snowstorms and sandstorms);
- *Hydrological* hazards, including inland flooding, coastal surge, wet mass movements (such as landslides and avalanche) and subsidence; and
- *Climatological* hazards, including extreme temperature (whether heat or cold waves), and wildfire.

2.1.3. End users and operators

When developing a DSS, it is important to understand who will use it and how they will use it. Consequently, DSS developers need to identify and understand the end users (those who will use the information) and operators (those who 'press the buttons') of the system. As part of the proposed classification system, the review categories for target operators and end users are divided into two types — their organisation and occupation — as shown in Fig. 3. The categories for organisation were adapted from Simpson et al. (2014). The categories for occupation, whether managers or professionals, is based on the International Standard Classification of Occupations (Integrated Research on Disaster Risk, 2014). The categories for organisation and occupation can be applied twice, once each for end users and operators, as these can be different.

2.1.4. Spatial and temporal information

DSSs may explicitly consider changes/variability in time and space. If they do, then the categorisation system considers their spatial extent and planning horizon, respectively (Fig. 4). In addition, if a DSS considers the future, the categorisation separates those that use static time slices of future periods from those that dynamically model through time.

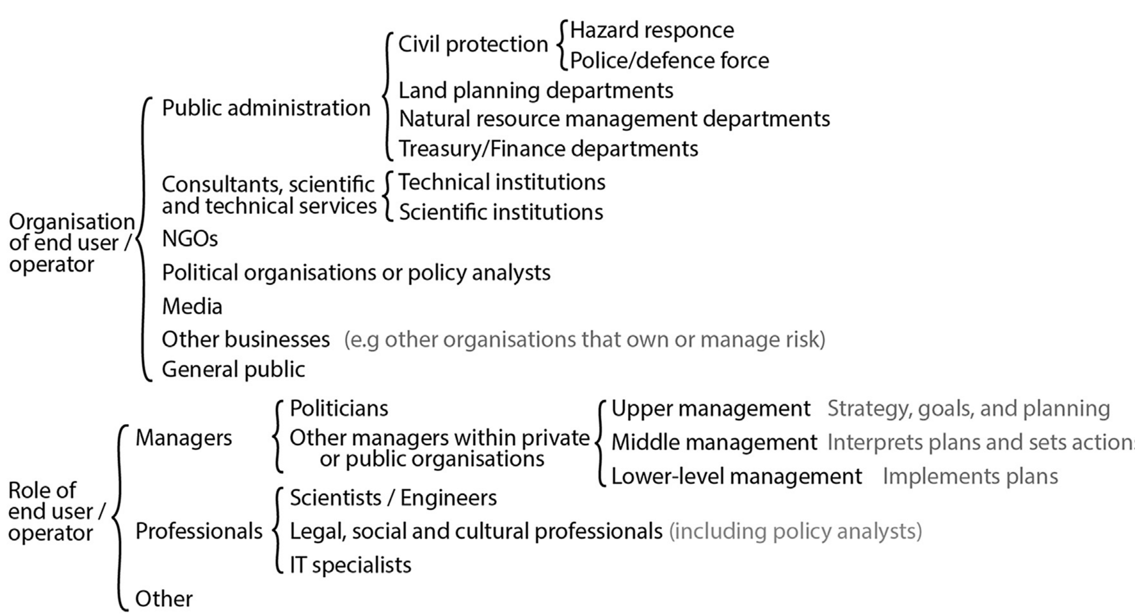

Fig. 3. Subcategories for end users and operators.

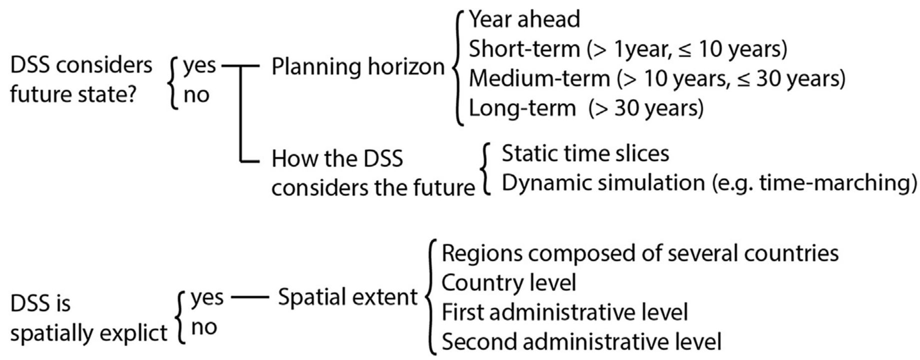

Fig. 4. Subcategories for spatial and temporal information. For geographic extent, administrative levels (first and second) are a global classification being the first and second level to which a country divides itself; delineations from the global administrative boundaries GADM database of Global Administrative Areas (Hijmans et al., 2015) were used.

2.2. Problem formulation

The components in the proposed classification system for problem formulation include the identification of risk-reduction options, external drivers and scenarios, and objectives and criteria. Further details on each of these components, as well as the specific assessment categories for each of these, are given in the following subsections.

2.2.1. Risk-reduction measures

DSSs can be developed to test different types of risk-reduction measures. By risk-reduction measure, we mean any activity or project that potentially reduces the impact or consequences of hazard events that is done before an event occurs. Subcategories for risk-reduction options were based on those suggested by Bouwer et al. (2014), in addition to measures that improve emergency response, as shown in Fig. 5.

2.2.2. External drivers

The performance of risk-reduction measures will change in the future due to external drivers. To assess these changes, DSSs can use future trajectories of input variables and parameters that are varied according to the influence of these external drivers. In the framework, five types of drivers are considered, using the *STEEP* framework (Bradfield et al., 2005), outlined below:

- **S**ocial (which includes urbanisation and the way in which people live — where they live, their social and geographical mobility, their wealth and the way this is shared — as well as demographic changes such as aging and growing populations);
- **T**echnological (which includes development of better communication, advanced analysis and prediction capabilities, smarter infrastructure, better integration of systems, and development of green infrastructure);
- **E**conomic (which includes economic growth, the effect of ageing infrastructure, increased reliance on communication and logistic networks, the geographical changes to manufacturing, commerce and business, and changes in finance available for risk reduction);
- **E**nvironmental (which includes the effects of climate change, in particular on the frequency and severity of extreme weather events, sea level rise, environmental degradation, and changed approaches to environmental management and urban design); and
- **P**olitical (which includes leadership priorities and how they change institutional capacity to manage risk, the strength of risk governance such as in urban development planning, trends in terrorism, the effect of privatisation on vulnerability, the effect of social media and crowdsourcing on risk-perception, building standards, and the effect of stakeholder engagement on risk-management policies, as well as competitiveness between

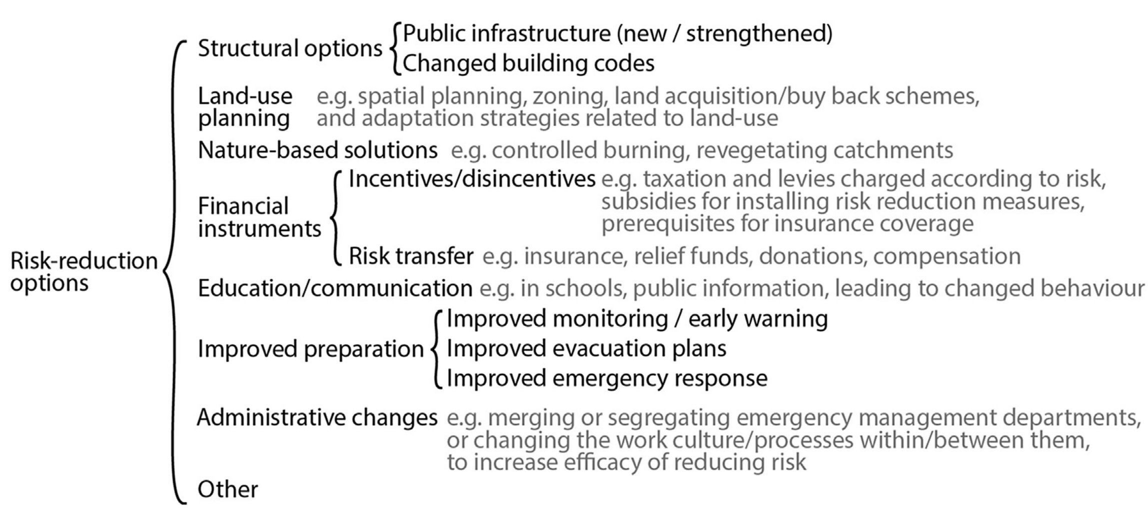

Fig. 5. Subcategories for risk-reduction options. This category is only relevant for DSSs that enable testing of risk-reduction options, as categorised in ‘Function and use’ (See Section 2.1.1).

cities — which may have very different risk profiles — for skills, investment and talent).

2.2.3. Decision indicators

To assess the effectiveness of different risk-reduction options, their performance needs to be evaluated against one or more objectives using indicators. As shown in Fig. 6, indicators are divided into economic, environmental, social and built environment subcategories, based on the EU seventh framework research project titled "New methodologies for multi-hazard and multi-risk assessment methods for Europe (MATRIX)" (Wenzel, 2012). The choice of the economic subcategories was also influenced by Meyer et al. (2013). Furthermore, methodological aspects were considered, in particular how criteria aggregated across hazard events with different return intervals, and how criteria considered temporal change.

2.3. Analysis framework

The proposed analysis framework classification system considers the selection of modelling components, the way these are integrated, and the way in which different risk-reduction options are explored. Further details on each of these components are given in the following subsections.

2.3.1. Model selection

Modelling based DSSs generally make use of one or more existing models in order to evaluate the impact of risk-reduction options (see Section 2.2.1) for one or more hazards (see Section 2.1.2) on the criteria corresponding to the selected objectives (see Section 2.2.3) for a particular scenario (see Section 2.2.2). To do this, models of hazard, exposure and vulnerability are needed, which can be developed using different approaches. The review categories for modelling are shown in Fig. 7, which cover aspects relating to model output, how time and space are represented, and the underlying modelling approach. As a DSS may comprise of multiple different hazard, exposure and vulnerability models, this classification can be applied to each of these in turn. The basis for this categorisation was developed in Daniell (2009, 2011, 2014), with the classification regarding spatiotemporal resolution based on Khazai et al. (2014) and van Delden et al. (2011b).

2.3.2. Screening through risk-reduction options and post-analysis of options

An analysis framework may also specify a strategy for developing and/or screening through risk-reduction options in order to help select portfolios of options that perform better with respect to planning objectives. Therefore, techniques may be included within the DSS that help identify well performing options from the space of all possible options and for comparing their performance (post-analysis of options). Numerous techniques are available for screening through risk-reduction options from manual trial-and-error approaches to formal optimisation approaches, and these were categorised according to this. If optimisation was included, this was categorised according to whether it was analytic or metaheuristic, and whether single or multi/many-objectives were considered.

Subcategories for post-analysis of options include the use of multi-criteria decision analysis and sensitivity/uncertainty analysis techniques. These techniques help decision makers understand the trade-offs they are making in choosing risk-reduction options, the robustness of these options and the uncertainties regarding their performance.

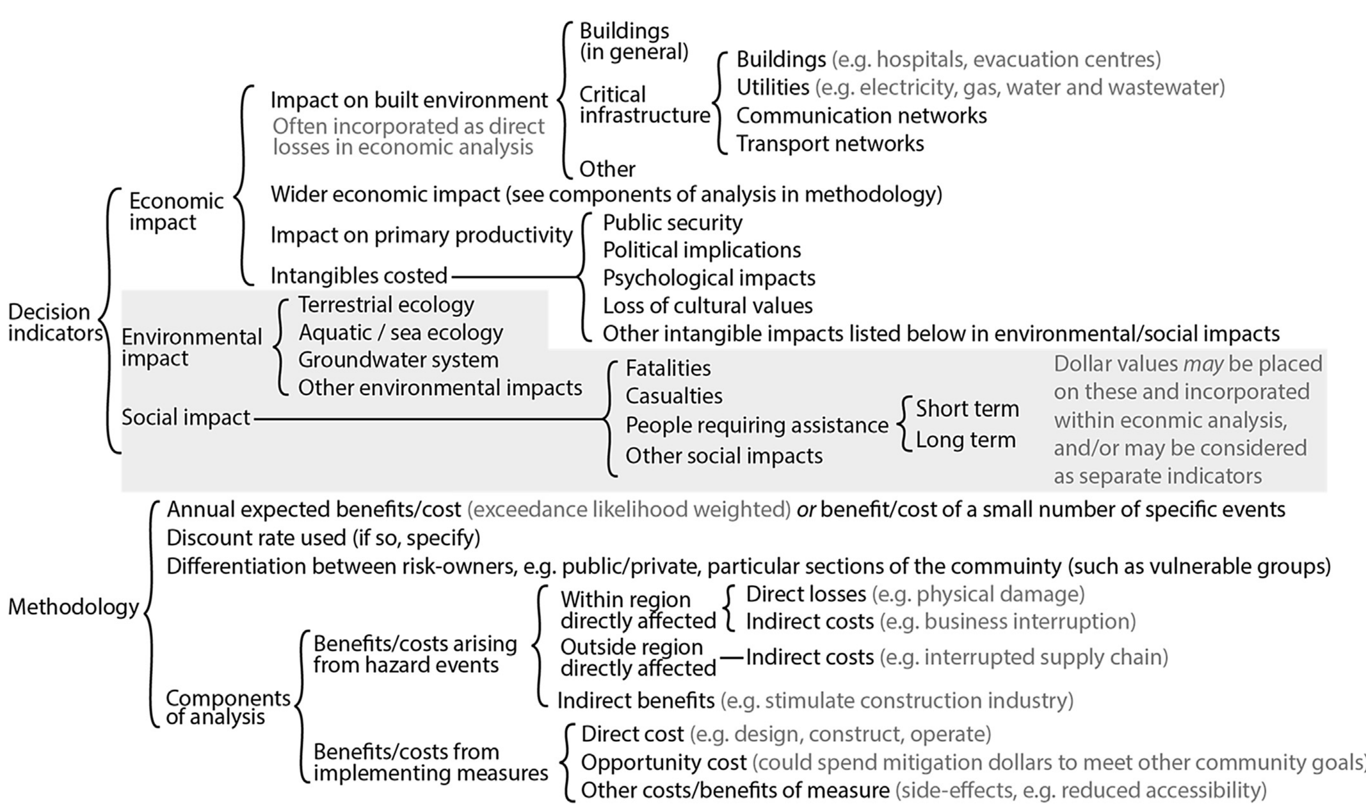

Fig. 6. Subcategories for decision indicators. This category is only relevant for papers that considered vulnerability in addition to hazard, which enables the impact on social, environmental and economic aspects to be calculated.

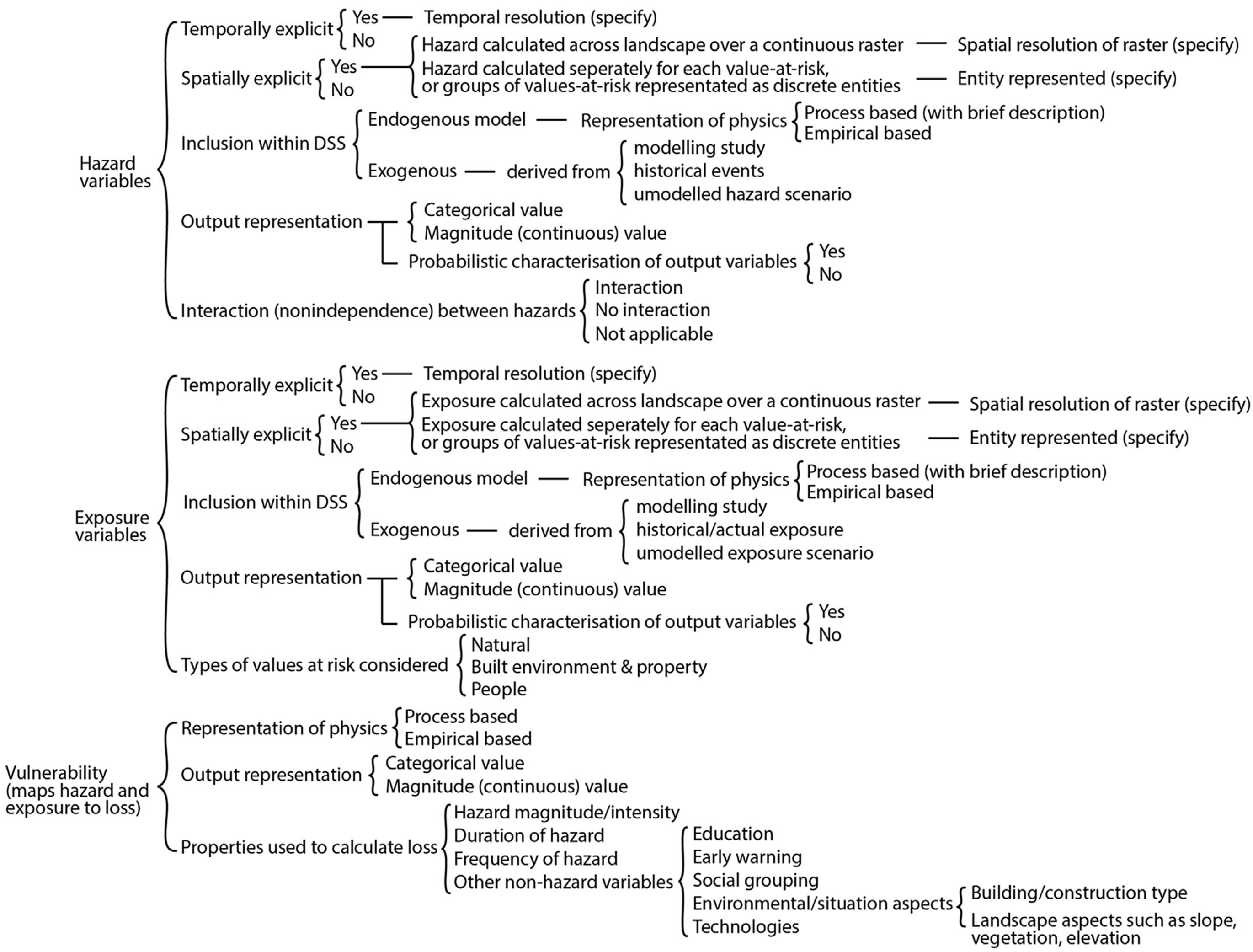

Fig. 7. Subcategories for modelling.

2.3.3. *Model integration*

Model-based DSSs tend to consist of an integrated model, of which components may be either pre-existing or bespoke. As part of the proposed classification system, the following categories considered the choice and development of modelling components:

- All modelling components are existing and were integrated as part of the DSS;
- The DSS made use of some existing component models; or
- All components were developed from scratch and integrated.

To classify the nature of the integrated model, the following frameworks, as identified by Kelly et al. (2013), were used:

- Systems dynamics framework;
- Bayesian network framework;
- Coupled component framework (models from different disciplines or sectors are combined to form an integrated model);
- Agent-based modelling framework; or a
- Knowledge-based framework (also referred to as expert systems).

2.4. *User and organisational interaction with the system*

Decision support systems exist to convey information in a user-friendly fashion. In order to do this, DSS architects need to consider what information to display, and how this information is derived from model outputs, in addition to the design of graphical user interfaces (GUIs). Further details on each of these components, as well as the specific review categories for each of these, are given in the following subsections.

2.4.1. *Specification of indicators for criteria, and their derivation from model output*

Once it has been identified who will be using the DSS and in what environment, the outputs of the integrated models (Sections 2.3.1 and 2.3.2) have to be mapped to the decision indicators (Section 2.2.3) required for decision-making and transformed/converted appropriately. With regard to risk-reduction planning, a pertinent decision variable is risk (i.e., an indication of the expected loss when considering both the likelihood and consequence of a hazard). Therefore, the following subcategories are included in the proposed classification system, categorising risk based on whether it is:

- Aggregated across events (i.e., in calculating an expected loss, as opposed to loss for a number of discrete events);
- Aggregated across time (and if so, what discount rate was used);
- Aggregated across space; and/or

- Aggregated across value types (e.g. across different types of values-at-risk, such as buildings and roads, across risk units, such as financial loss and lives lost, and across hazard types, such as earthquake and flooding, or kept separate).

2.4.2. Software architecture, graphical user interface design and development

Graphical user interfaces (GUIs) should be designed so that the risk-reduction options of interest can be explored and the desired outputs can be obtained intuitively. As part of the proposed classification system, subcategories include whether the GUI contains:

- A system for interactive manipulation of model parameters, selection of inputs and development of integrated scenarios;
- Tables;
- Maps; and/or
- Charts.

With regard to GUI development, subcategories indicate whether:

- Stakeholders were involved in GUI design;
- The interface was designed for different DSS users (such as separate interfaces for policy analysts and scientists);
- External software frameworks were used for development; and
- The software is deployed as a desktop application or accessed and used via a website.

With regard to software frameworks, subcategories indicate whether the DSS was built on top of an external application shell, and whether the application depended on external dependencies, as shown in Fig. 8.

2.5. Use and user engagement

A successful DSS is one where users have taken ownership of the product. In order for this to occur, engagement with users during both development and use processes is critical. As pointed out by Van Delden et al. (2011a, b), engagement is vital “not only to ensure that their input is included in development, but also because including them enables social learning on the side of the users as well as on the developers' side (scientists and IT specialists). It is unrealistic to demand from users that they provide a detailed specification document at the beginning of the design and development process, simply because they are not aware of what can be expected and what limitations have to be taken into account” (van Delden et al., 2011a). Consequently, categories have been developed for both the DSS development and use processes, as given in the following two subsections.

2.5.1. Development process

Development process subcategories include whether end-user engagement had occurred and whether there was an iterative development process, as shown in Fig. 9.

2.5.2. Use process

Subcategories for the use process were based on relevant aspects mentioned in van Delden et al. (2011a) and include whether systems have been used across multiple case studies and how the use process was undertaken, as shown in Fig. 10.

2.6. Monitoring and evaluation

The subcategories for monitoring and evaluation of the utility of the DSS, as shown in Fig. 11, were based on van Delden et al.

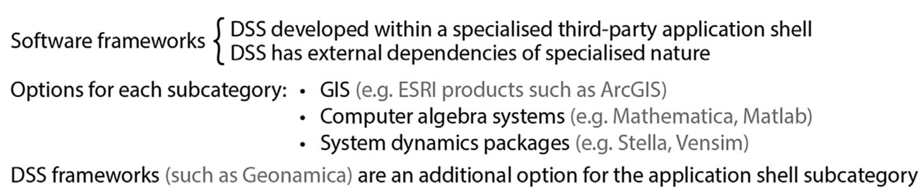

Fig. 8. Subcategories for software frameworks. Citations for software are: Environmental Systems Research Institute (ESRI) (2016) for ArcGIS; The MathWorks Inc (2016) for MATLAB; Wolfram Research Inc (2016) for Mathematica, ISEE Systems (2016) for STELLA; Ventana Systems (2016) for Vensim; and Research Institute for Knowledge Systems (RIKS) (2016) for Geonamica.

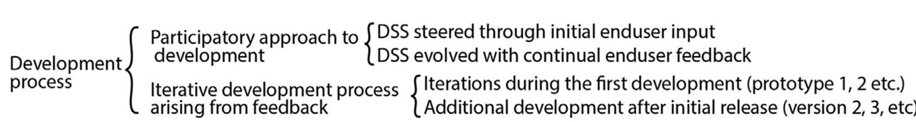

Fig. 9. Subcategories for the development process.

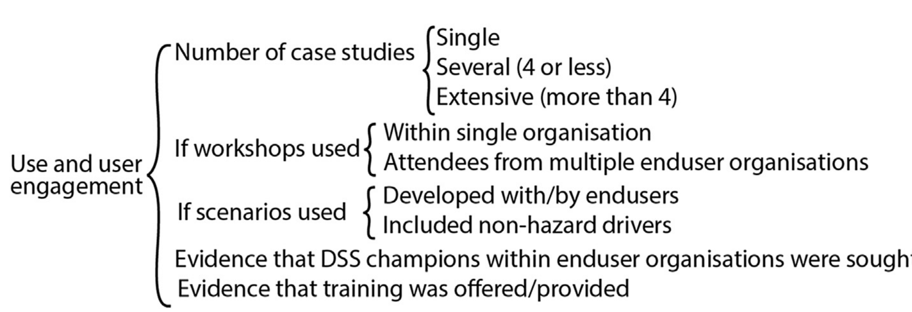

Fig. 10. Subcategories for use process.

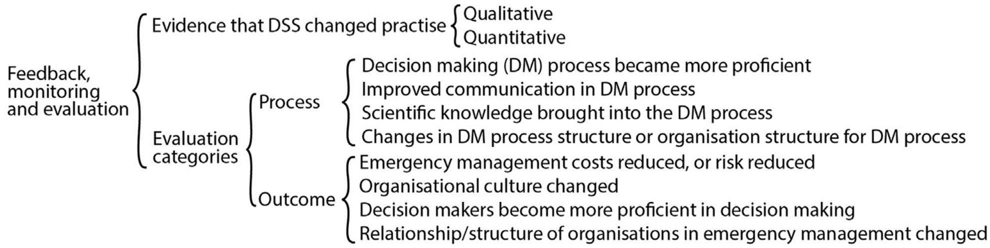

Fig. 11. Subcategories for monitoring and evaluation.

(2011a), and include whether the DSS helped change. In addition, the nature in which the DSS changed practise was assessed using subcategories derived from Phillips-Wren et al. (2004).

3. Selection of papers for review

Papers selected for review were identified using the search tools through the Web of Science database (Thomson Reuters, 2016). The search query is illustrated in Fig. 12 and explained in the following. For a paper to be identified from this search query, it needed to contain a keyword pertaining to DSSs, (left-most box of Fig. 12), a keyword pertaining to natural hazards, (centre box of Fig. 12), and a keyword pertaining to risk reduction, (right most box of Fig. 12). Additional DSS papers cited by those found using this search query were also identified for consideration. In total, 101 peer reviewed papers, published in leading and sufficiently high impact journals, were chosen for review. It should be noted that only papers in international peer-reviewed journals were considered as the primary goal of this paper is to identify research gaps and future research directions, as stated in the objectives outlined in Section 1. A more detailed explanation of the selection methodology is given in Appendix A, while a list of the 101 papers, the DSSs they refer to and software/code availability is provided in Appendix B.

Fig. 13a shows the spread of publications by year published, which indicates a consistently increased publication rate since the 2004–2007 interval. This trend of an increased focus on research and development in natural disaster risk-reduction DSSs is further highlighted by the increased relative frequency of publications when indexed by the number of articles within the Web of Science database (Fig. 13b).

In general, it was found that the papers identified for the review were of three types:

1. The majority of papers were those that introduced an integrated software system for decision support.
2. A second class of papers introduced or developed a technique that could be incorporated within a DSS. These techniques ranged from multi-criteria decision analysis tools, modelling techniques for estimating hazard, to methods for sifting through data in order to infer knowledge/information required to make decisions. Most often these papers only discussed the utility of the technique within a broader DSS, and did not test the technique within the context of a DSS.
3. In the third class of papers, an already developed DSS was applied to a case study. These papers were primarily focussed on knowledge gained about risk in the case study area, rather than on the design of the DSS itself.

4. Review of decision support systems for natural disaster risk reduction

As part of the review process, the selected papers (see Section 3) were assessed against the criteria developed in Section 2. The results of these analyses are presented and discussed in the following sub-sections.

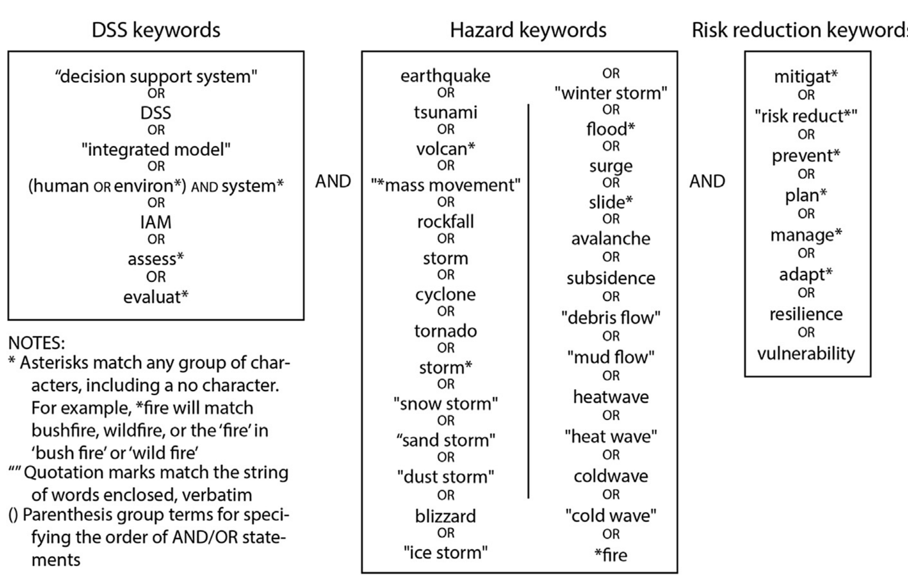

Fig. 12. Search terms used to identify papers to review.

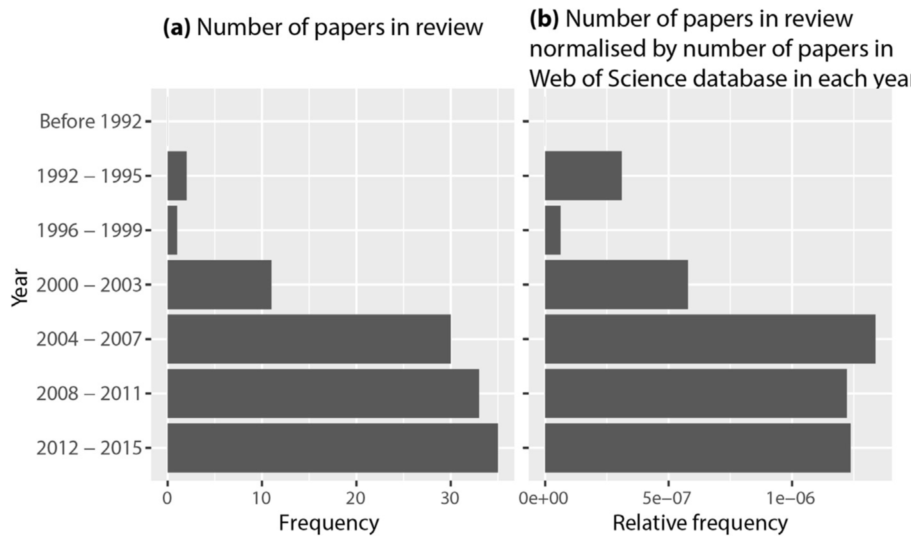

Fig. 13. Publication dates for papers reviewed (a) by frequency, (b) by relative frequency through normalisation with the number of papers published within the years in each bin.

4.1. Scoping

4.1.1. Function and use

Fig. 14 shows the spread of papers by DSS purpose, revealing that most DSSs (83% of those surveyed) could identify areas of risk. This was consistently achieved in the DSSs through the use of spatially explicit hazard models. Fifty-seven percent of the DSSs were able to predict the implications of hazard through the use of vulnerability models; likewise around half (48%) of the DSSs were designed to test mitigation options. That is, the interface allowed the user to select mitigation options for testing, and the DSS would manipulate the model structure and/or inputs and parameters to simulate the effect of such options. In contrast, few DSSs had inbuilt functionality to explore acceptable levels of risk (5 DSSs), make plans into the future (9 DSSs), or identify/suggest risk-reduction portfolios (8 DSSs). These decision tasks require additional functionality within the DSS, such as the ability to simulate into the future reflecting the influence of external drivers, to develop trade-offs between risk and other community objectives, and to develop expert systems.

Work required in developing these functionalities may involve additional source-code and data for enabling simulation along future trajectories, the integration of additional modelling components to assess the impact of mitigation options on other community objectives, and the inclusion of optimisation, inference systems and other artificial intelligence/operations research techniques to develop expert systems, in addition to the development of additional graphical user interface components and further end-user participation as part of the development process. The significant amount of work required for this might be the reason why DSSs with these functionalities were less frequently observed within the selected papers.

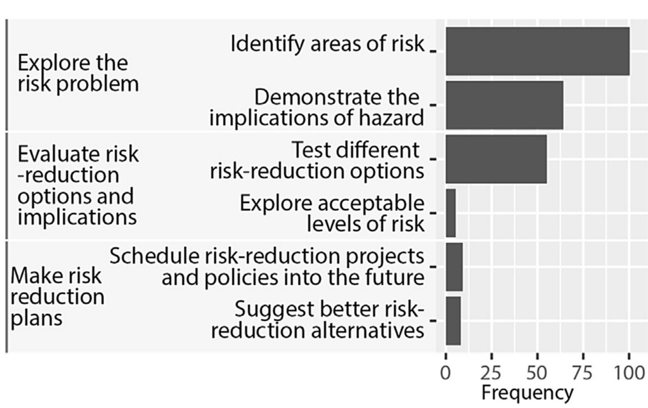

Fig. 14. Frequency of DSSs by purpose within the papers reviewed.

4.1.2. Hazards

The frequency with which different hazards were considered and the geographical distribution of the case studies considered are shown in Fig. 15. Amongst the hazards, flooding, fire, earthquake received much attention (35, 24, 23, and 23 papers respectively), with much less work on drymass (4 papers) and wetmass movements (9 papers), storms (11 papers), volcanoes (1 paper) and extreme heat/cold (2 papers). With regard to flooding, fluvial flooding and coastal surge were given much more attention than pluvial flooding. The distribution and severity of each hazard type are also shown in Fig. 15, demonstrating that more case studies were located in regions of heightened risk, particularly for flood. However, few DSSs have been developed for use in Africa and South America.

Most of the reviewed papers only considered a single hazard. However, Woodward et al. (2014), Yang et al. (2011), Zagonari and Rossi (2013), Harrison et al. (2012), Mokrech et al. (2009) Scawthorn et al. (2006) and Yu et al. (2014) considered both coastal surge and fluvial drivers of flooding, while Pagano et al. (2014) and Tralli et al. (2005) considered landslides and flooding, and Piatyszek and Karagiannis (2012) considered both storm and flooding. In addition, the software packages HAZUS-MH (Schneider and Schauer, 2006), InaSAFE (Pasi et al., 2015; Pranantyo et al., 2015) and RiskScape (Schmidt et al., 2011) are multihazard DSSs that incorporate more than three hazard types. In all of these cases, hazard occurrence between the hazard types were treated as independent.

4.1.3. End users and operators

Fig. 16 shows the spread of end users for the 77 DSSs detailed in the papers reviewed. Of these, there were 17 where the end user was not explicitly outlined. When end users could be reasonably surmised, they were often situated in organisations near the frontline of risk reduction, as shown in Fig. 16a: response departments (43%), land management departments (34%), land planning departments (39%) and technical institutions (such as

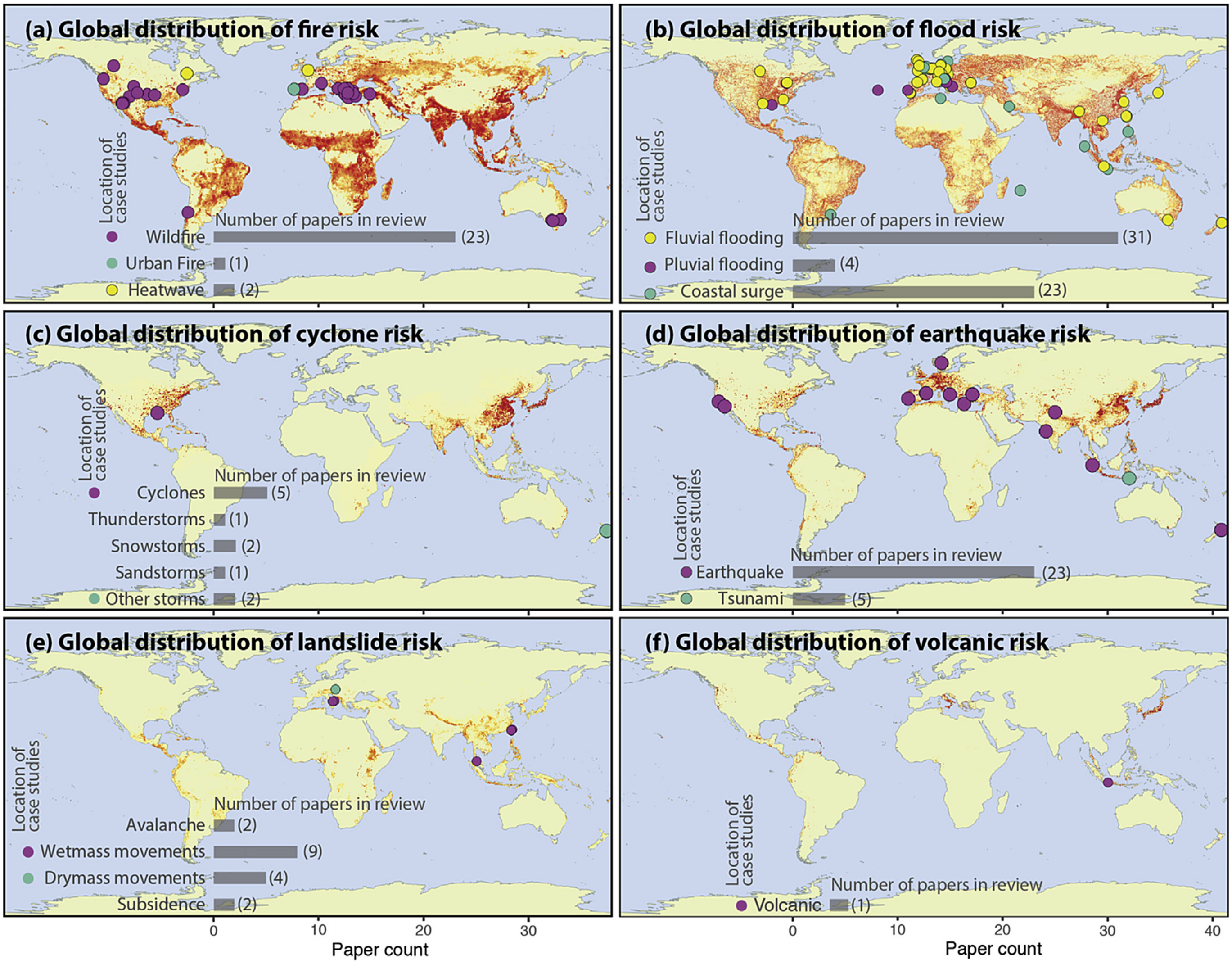

Fig. 15. Global distribution of natural hazard risk, and location and frequency of case studies within the papers reviewed, for each hazard type. Data for global distributions of risk for each natural hazard were obtained differently, as follows. Fire risk was derived from historical fire location and population density, with historical fire locations sensed by the European Space Agency's Advanced and Along Track Scanning Radiometer (ATSR) World Fire Atlas (algorithm 2) mission, and population density from (Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2005). Risk for flood, cyclone, earthquake, landslide and volcanic were calculated based on the economic exposure and respective hazard dataset from the 2015 United Nations global assessment report (Cardona et al., 2015).

consultants) who are interested in designing or investigating risk-reduction solutions (34%). However, there was limited effort in designing DSSs for treasury/finance departments (5%), business (4%), political organisations (4%), and relief organisations (1%). Interestingly, while not as close to the front-line of risk reduction, the influence of some of these organisations on the risk a community is exposed to can be profound, for example, treasury/finance departments which stipulate the amount of funding allocated to risk-reduction organisations and how funds should be spent. Fig. 16b shows the target roles of end users and operators within their organisations. Ninety-two percent of end users were managers, although it was often unspecified what level of management they were specifically targeted at. When the level of management could be identified, it was usually middle management, which was expected, as the role of middle management is to interpret high-level goals from upper management (i.e. regarding risk reduction) and develop strategies (i.e. mitigation) to achieve these. However, DSSs could also be tailored for professionals and lower level managers who may be more involved in the detailed design/implementation of measures or upper management whom tend to be more involved in prioritising focus between different hazards and choices regarding the trade-off between risk and other community goals. Regarding operators, 50% of DSSs were aimed at technical personnel, reflecting the skills and knowledge required to operate many of the DSSs. The remainder were also specifically designed for non-technical operators where technical details were sufficiently developed and inbuilt within the DSS so to allow them to be hidden behind a policy/project-centric interface.

4.1.4. Planning horizon

Only 27 (22%) of the reviewed papers reported or demonstrated an ability to consider the future within the DSS (Fig. 17a). Of these papers, the proportions that considered long-term, medium-term and short-term planning horizons (length of time into the future considered) are shown in Fig. 17b. As can be seen, the majority of the papers (69%) considered longer term planning horizons, and this reflects that many risk-reduction options are long-term — for example structural options and land-use planning (See section 4.2.1).

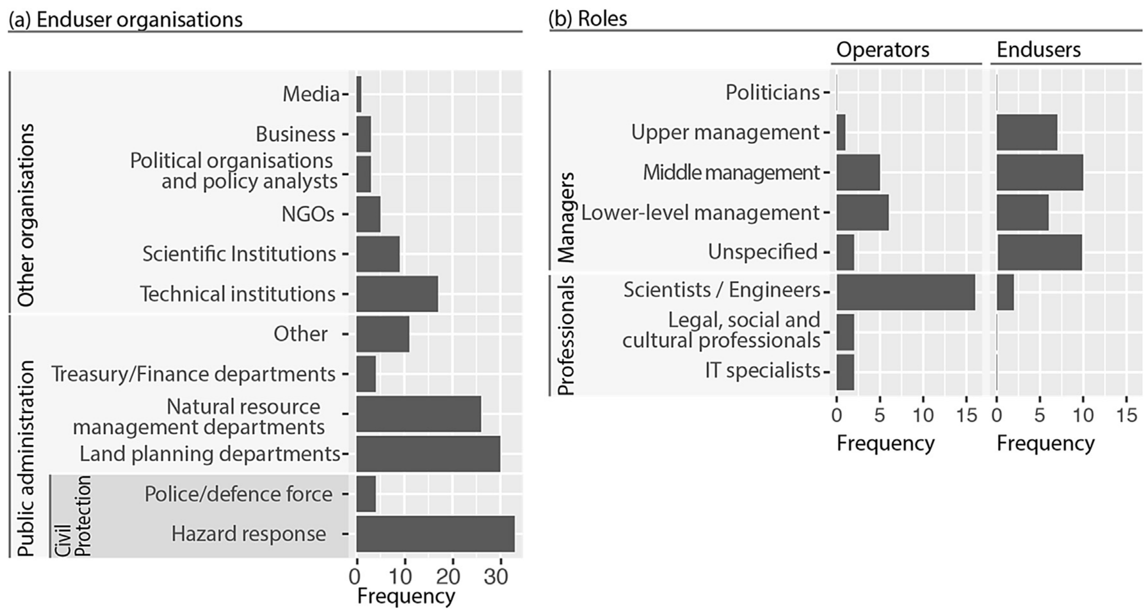

Fig. 16. Identified end users and operators of DSSs in the papers reviewed. End users are those who use the information arising from the system, and are often distinct from operators who are those that 'press the buttons' of the system.

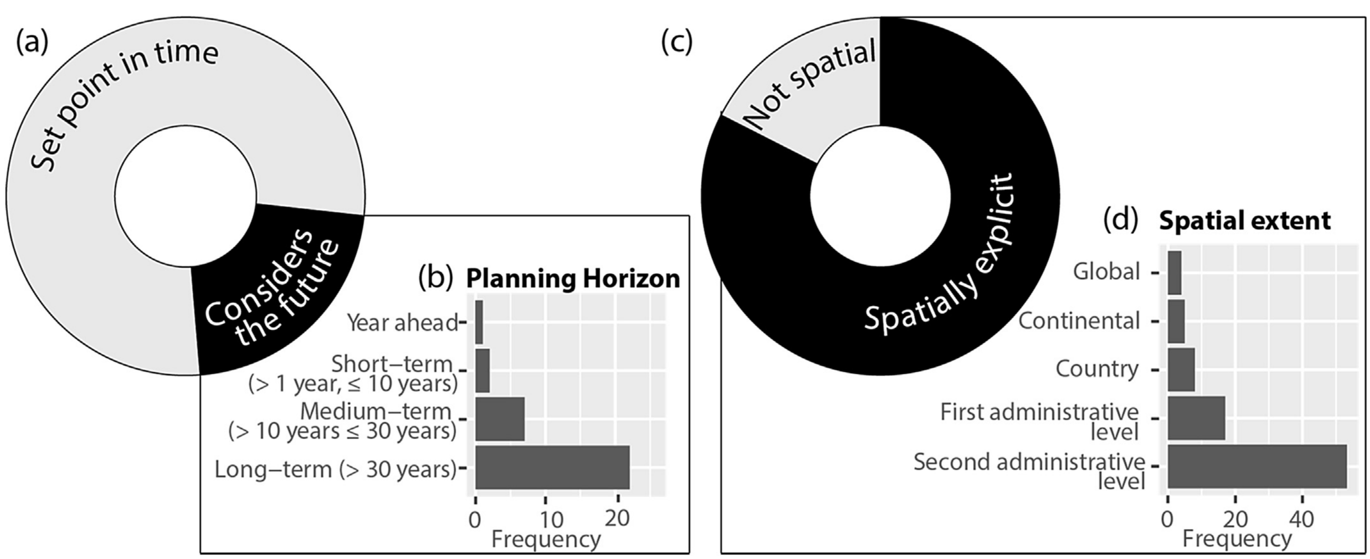

Fig. 17. Spatial and temporal specifications of modelling in the papers reviewed.

4.1.5. Geographic extent

The geographical extent and spatial resolution of reviewed DSSs are also shown in Fig. 17. As can be seen, 83% of DSSs were spatially explicit (Fig. 17c). Fig. 17d shows that case studies at smaller geographic extents were considerably more prevalent than those at larger extents (60% of case studies were implemented at the second administrative level, or smaller).

4.2. Problem formulation

4.2.1. Risk-reduction options

DSSs that were able to test different risk-reduction options were included in 64 of the reviewed papers. As can be seen in Fig. 18, a relatively large number of DSSs was able to be used to test the benefit of natural resource management (31% of DSSs surveyed), land-use planning (32%) and public infrastructure (36%) for risk reduction. In addition, there was a relatively large number of DSSs that were able to consider the benefits from improved emergency response (23%) and evacuation plans (18%), and improved monitoring and early warning (22%). However, there were few DSSs that considered the potential of financial incentives (5%) or the inclusion of risk transfer such as insurance (8%), building codes (13%), education (10%), or administrative changes (1%). These results appear consistent with the options that end users and organisations would likely have influence over, as described in Section 4.1.3.

4.2.2. Objectives and criteria

Only 15 DSSs considered hazard without taking exposure and vulnerability into account (Fig. 19a); taking exposure and vulnerability into account is required to fully consider the dimensionality

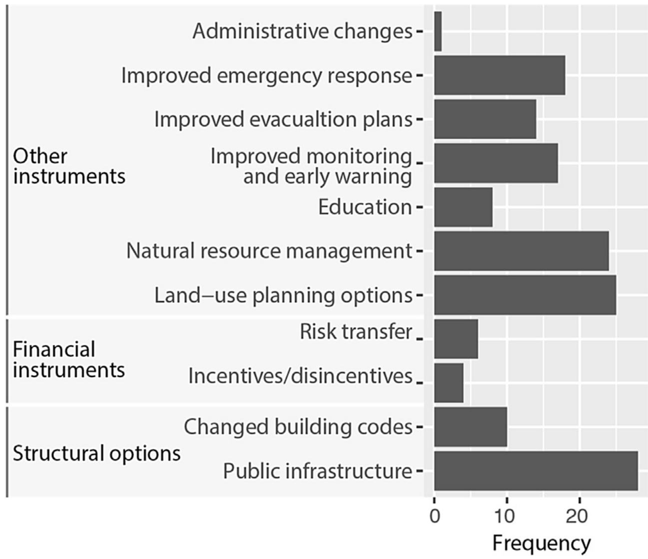

Fig. 18. Risk-reduction options that were included in the DSSs described in the papers reviewed.

of risk. For the papers that did develop risk based criteria, the type of criteria used are shown in Fig. 19b. Economic criteria were most frequently used (i.e. in 57 papers), although social and environmental criteria were also widely adopted (in 38 and 28 papers respectively), which is important due to the catastrophic impact hazards can have on communities and their environment. Intangibles (placing monetary values on items for which a market valuation does not exist) were less widely included within economic analysis (10 papers).

4.2.2.1. *Economic criteria.* The frequency with which DSSs calculated damage losses from primary productivity and the built environment is displayed in Fig. 19c. Predictions of loss most often included building damages, and these are often the main contributor to loss. Seven papers also looked at critical infrastructure such as utilities, public buildings such as hospitals or transport networks, while only Noonan-Wright et al. (2011) considered communication networks.

Only nine papers considered intangible aspects of risk. One of these considered political implications (The loss of credibility of local authorities in Lindell and Prater, 2006), three considered loss of cultural values (i.e. Ahmad and Simonovic, 2001; Assilzadeh et al., 2010; Morehouse et al., 2010), two considered safety (i.e. Levy, 2005; Yadollahi and Zin, 2012), Zanuttigh (2011) and Hinkel and Klein (2009) included a number of social, cultural and environmental factors, while Morehouse et al. (2010) also considered 'wilderness, beauty and isolation'.

4.2.2.2. *Environmental criteria.* Of the twenty-eight papers that included environmental criteria, twenty-two assessed the impact on the terrestrial environment, twelve papers considered impact on aquatic environments and only three papers included other environmental criteria beyond these (Fig. 19d), such as air quality (Noonan-Wright et al., 2011), inundation in environmentally protected areas (Rodrigues et al., 2002), and changed topography (Tralli et al., 2005).

4.2.2.3. *Social criteria.* Of the thirty-eight papers that included a social criterion, fatalities were the most common indicator, included in twenty-two papers, as shown in Fig. 19e. Thirteen papers included casualties and six papers considered people who were not necessarily injured, but required long- or short-term assistance post-hazard. Amongst the hazards, these social criteria

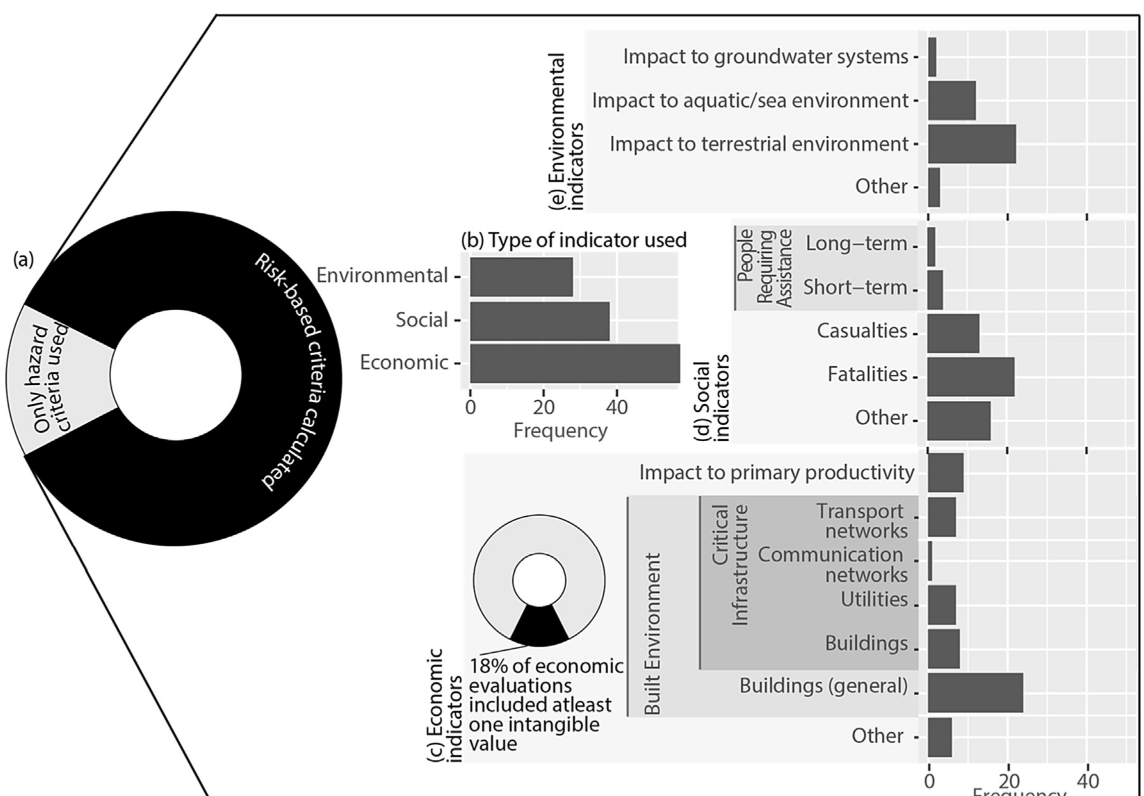

Fig. 19. Criteria used for assessing objectives, as well as their components, within the reviewed papers.

were often used for earthquake loss assessments. Three papers considered the unequal impact of hazards on different ethnic, demographic, or regional populations. A wide variety of other social indicators was also used, including health (Nauta et al., 2003; Zagonari and Rossi, 2013), social distress (Zagonari and Rossi, 2013), issues of equity (Levy, 2005), evacuation upheaval (Melo et al., 2014), homelessness and displacement (Anagnostopoulos et al., 2008; Haldar et al., 2013) and loss of public services (Nauta et al., 2003; Pagano et al., 2014).

4.2.2.4. Assessment methodology. Amongst the reviewed DSS papers, if a risk assessment was conducted, then this always included direct losses (Fig. 20). Sixteen studies also included indirect costs from hazard events and ten included the cost of implementing risk reduction. No studies considered the indirect benefits from hazards events, or the side effects, whether positive or negative, of implementing risk-reduction measures.

4.2.3. External drivers and scenarios

Across the reviewed papers, future scenarios included climate, demographic, economic and political drivers, as shown in Table 1. In 17 papers climate was a driver for the hazard model. In nine papers, demographic changes were considered for modelling exposure, while three papers (de Kok et al., 2008; Xu et al., 2007; Zanuttigh et al., 2014) also used economic projections as a driver for change in exposure. In Toutant et al. (2011) and Manley and Kim (2012), demographic changes also drove vulnerability into the future. Mokrech et al. (2009) was the only author to include a political driver, where scenarios were developed to compare risk between global and local economies, and three papers considered technological drivers for change.

4.3. Development of analysis framework

4.3.1. Model selection

Fig. 21 shows the frequency with which different aspects of hazard, exposure and vulnerability were included. Hazard was considered in all DSSs, and endogenously modelled in 54 of the 77 DSSs, while exposure and vulnerability were considered in 58 DSSs.

4.3.1.1. Hazard modelling. Hazard modelling was based most commonly on spatially distributed, dynamic and process based modelling of disaster events, often using a number of different modelling strategies that were interconnected to assess risk behaviour. For example, Ahmad and Simonovic (2006); de Kok et al. (2008); Levy (2005); Nauta et al. (2003) and Yu et al. (2014) included temporally-continuous modelling of rainfall-runoff hydrology, paired with hydrodynamic modelling of flood inundation and damage curves for quantification of risk. Of the DSSs considered, 30 provided a continuous magnitude output of the hazard variables, while 39 provided a categorical hazard intensity rating.

In contrast, 23 DSSs did not involve hazard modelling. For example, some DSSs used historical or remote sensing data to characterise hazard (e.g. Tralli et al., 2005; Vafeidis et al., 2008), and some developed decision support techniques that did not require inbuilt hazard models (rather exogenous hazard data is entered, e.g. Akay et al., 2012; Alçada-Almeida et al., 2009; Bernknopf et al., 2006; Lindell and Prater, 2006; Manley and Kim, 2012; Piatyszek and Karagiannis, 2012; Rodríguez et al., 2011; Toutant et al., 2011; Vacik and Lexer, 2001; van Dongeren et al., 2014; Yadollahi and Zin, 2012; Zagonari and Rossi, 2013).

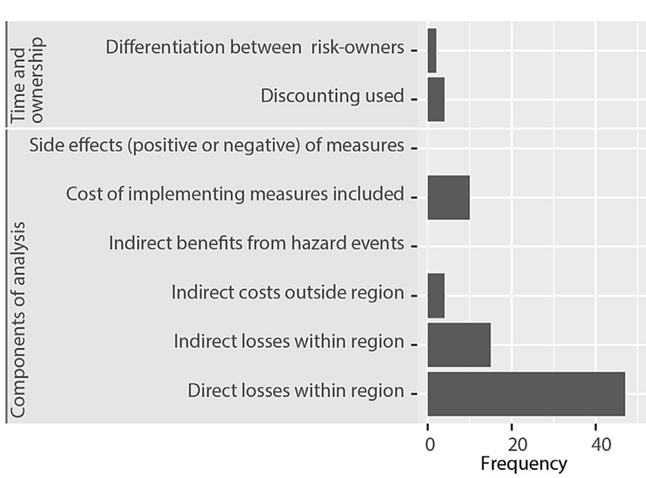

Fig. 20. Frequency with which studies differentiated risk across time and between risk-owners, and the components included in risk analysis.

Table 1
Number of papers that included different types of external drivers (STEEP) that were used to explore future changes through modifying different aspects of the risk calculation (Hazard-vulnerability-exposure).

Model component	Future driver				
	Social	Technological	Environmental	Economic	Political
Exposure	9	–	–	6	1
Hazard	–	–	17	–	–
Vulnerability	2	3	–	–	–

4.3.1.2. Exposure modelling. Of the 58 DSSs that included exposure information, only Manley and Kim (2012) derived exposure through a modelling approach in which an agent-based model was used to characterise human movement through buildings under hazard attack. The remainder used static maps of exposure variables: seven of these developed future exposure maps through scenarios, land-use plans, and/or expert knowledge. There was a relatively even spread in the types of exposed values that were considered: 17 papers included the location of natural values, 21 included the location of infrastructure and property, and 20 included the location of people (note that many DSSs include two or more of these exposure types).

4.3.1.3. Vulnerability modelling. Fifty-eight DSSs included vulnerability relationships, with most of these using susceptibility curves, which are empirically derived formulations directly linking loss to hazard intensity, although duration and frequency of hazard were also used (8 DSSs each), usually to calculate damage to environmental assets (e.g. in Zanuttigh et al., 2014, duration was a factor for calculating erosion, and frequency was a factor in calculating ecosystem disruption for storm hazard). The two papers that used process based modelling of vulnerability included evacuation models that were used to characterise social vulnerability in flooded areas (Kim et al., 2011; Lindell and Prater, 2006).

4.3.2. Model integration

Fifty-three percent of papers detailed an integrated modelling approach (Fig. 22a). As shown in Fig. 22b, for those that provided information on model integration, there was a reasonably even spread in the degree to which pre-existing modelling components were used; from those developing all their modelling components from scratch to those using only existing components. Fig. 22c shows that integration was most commonly achieved through a direct input/output coupling between components. Only nine of the DSSs used a knowledge based, agent based or Bayesian network framework for integrated modelling.

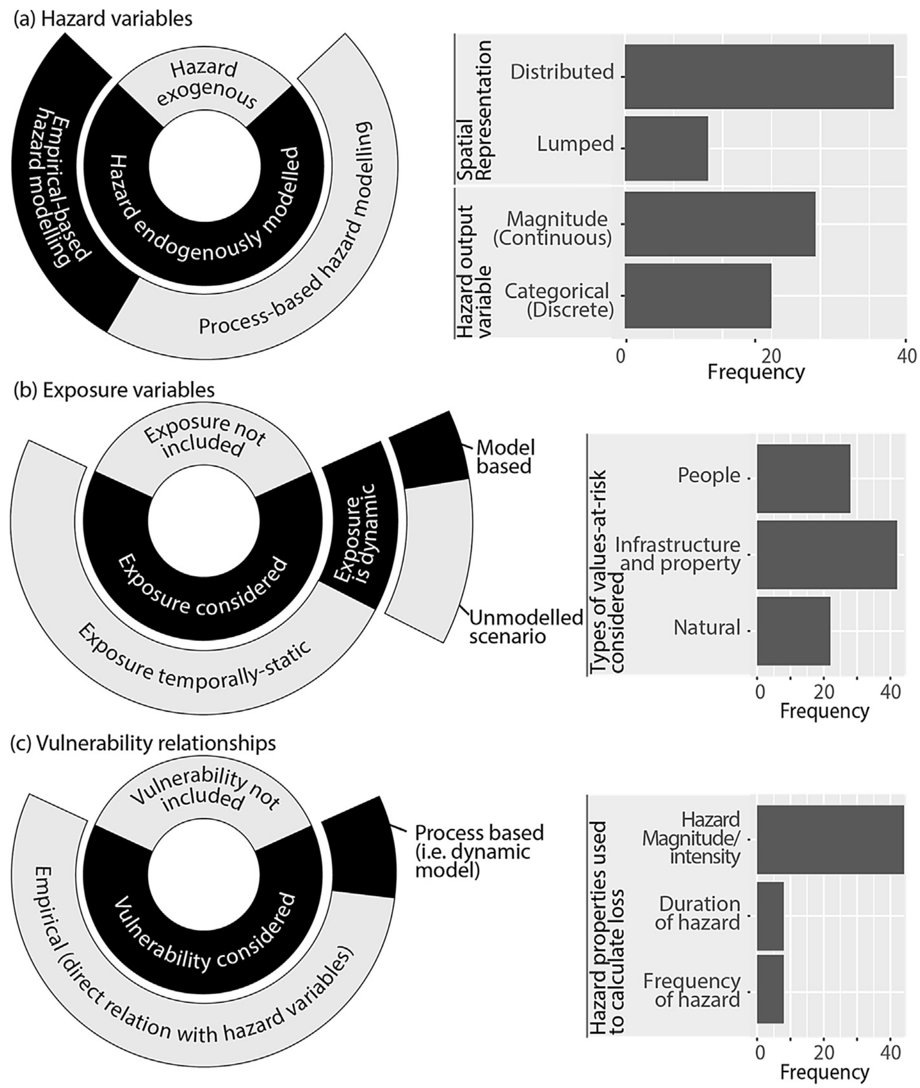

Fig. 21. Composition of the risk modelling components in the reviewed papers.

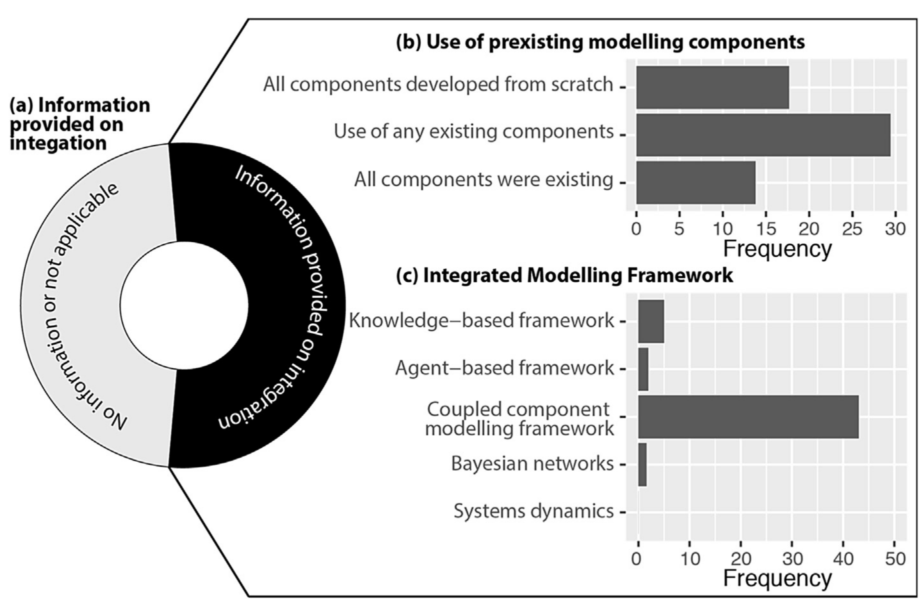

Fig. 22. The frequency with which DSSs used pre-existing or bespoke modelling components, and the means of integrating modelling components for the papers reviewed.

4.3.3. Exploration strategy for selection of risk-reduction options

Only eight of the reviewed DSSs included optimisation to sift through and locate favourable risk-reduction options. Of these, five were multi-objective using metaheuristic techniques, such as genetic algorithms. Nineteen of the DSSs included sensitivity/uncertainty analysis capability on the impacts of hazards and effectiveness of risk-reduction interventions, while 16 included multi-criteria decision analysis for the selection of risk-reduction options (see Fig. 23).

4.4. User and organisational interaction with the system

4.4.1. Mapping model output to decision-relevant criteria

Eighteen DSS papers reported on how decision criteria were derived from model outputs, which is less than a third of the papers for which this category was relevant (i.e. papers that presented a complete DSS). Of the papers that aggregated risk (across space, time, hazard events, or hazard types) and mapped this into a decision criterion (as shown in Fig. 24), only Ahmad and Simonovic (2001) discounted across time. Most papers aggregated across events to calculate a measure of expected losses, and 10 aggregated across multiple types of values at risk. Around half aggregated risk spatially.

4.4.2. Software architecture, GUI design and development

As shown in Fig. 25, all of the seventy-seven DSSs had a graphical user interface. Regarding the display of information within the interface, 33 DSSs included tables, 55 included geographical maps and 27 included charts. Only 13 demonstrated the involvement of end users in the design of the interface, and one included multiple interfaces for different levels of detail and types of analysis' required (Holman et al., 2008b).

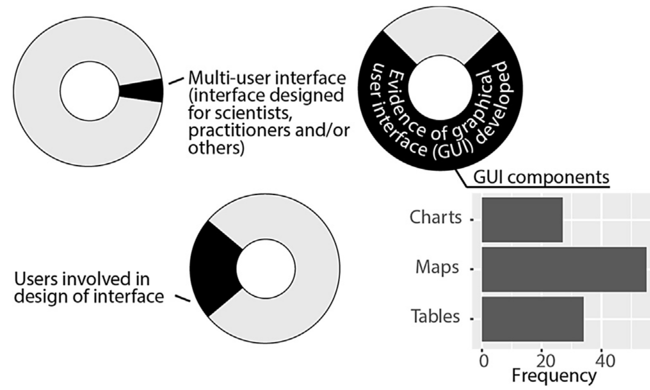

Fig. 25. Components and end-user involvement in graphical user interfaces design in the papers reviewed.

The software frameworks used within the reviewed papers for developing DSSs are shown in Table 2. Consistent with the number of spatially explicit DSSs that included maps, GIS packages were heavily drawn upon either as an external dependency, or as the application shell within which the entire DSS was contained. There were also 11 DSSs that used system dynamics packages or computer algebra systems. However, most DSSs were standalone applications.

4.5. Use and user engagement

While most of the 77 DSSs presented were designed to be

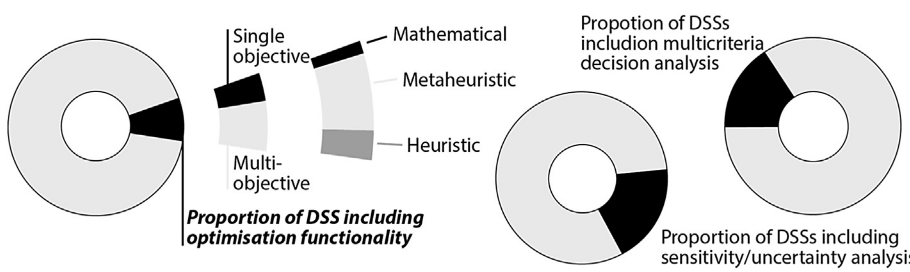

Fig. 23. Proportion of reviewed papers with tools for advanced exploration of risk-reduction options.

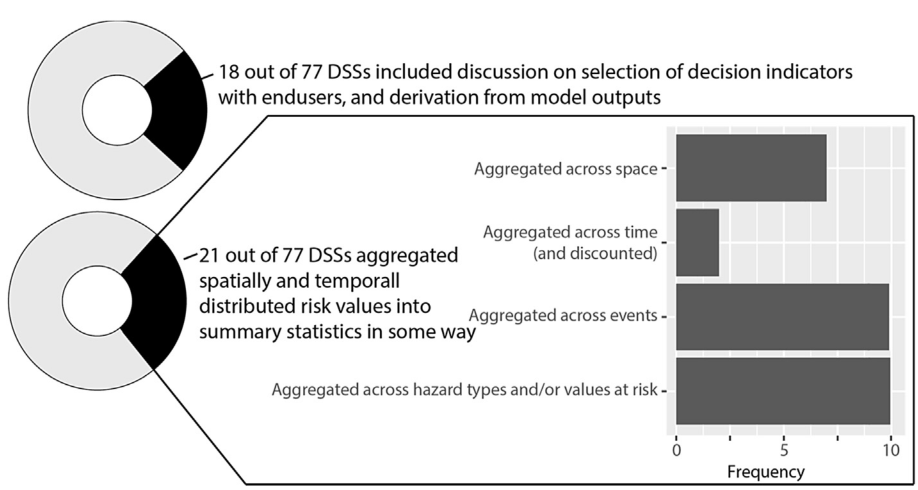

Fig. 24. Proportion of papers that discussed the development of decision criteria and their derivation from model results, and frequency of papers that aggregated risk across value-types, hazards, time and space.

Table 2
Software frameworks used for DSS software development in the papers reviewed.

Software framework	Used as application shell	External dependency
GIS	22	15
Computer algebra systems	6	3
Decision support system frameworks	4	N/A
System dynamics packages	0	2
Spreadsheets	2	1

generic, only 28 were reportedly used beyond a single case study in the DSS papers reviewed, and only 11 were used across more than four locations (see Fig. 26a). For many DSSs, generality of the software was not a development concern, as they were highly tailored to issues within a particular region (such as the Elbe-DSS used in de Kok et al., 2008).

While 26 DSS papers reported on the use of scenarios, most of these were hazard scenarios (e.g. flood events of different magnitudes). Only eight papers developed scenarios incorporating non-hazard drivers, which are helpful in understanding how risk-reduction portfolios perform across key uncertainties such as climate change (Fig. 26b).

Only three case studies displayed evidence that champions were sought, and only seven reported that end-user training occurred.

Some papers reported on the influence of end users during the development of a DSSs, as evidenced by the number of papers where DSS development was steered by or evolved with end-user input (11 papers each, Fig. 26c).

4.6. Monitoring and evaluation

The number of papers which reported activity under the monitoring and evaluation subcategories is shown in Fig. 27. As can be seen, there was minimal reporting on the utility and impact of DSSs on decision-making processes post-implementation. Only three gave quantitative and five gave qualitative information that DSS use had changed practise. The number of papers that reported specific improvements to the management of natural hazards is given in the bottom half of Fig. 27. More papers reported on changes the DSS made to decision making processes, rather than the long-term effect they had on risk management outcomes.

4.7. Summary

In order to provide an easily accessible overview of the main findings of the results of the review, the level of coverage of the different categories included in the review is summarised in Fig. 28. For each item in the figure, the amount of coverage within the review papers is summarised using a 'traffic' light indicator. These indicators correspond to the proportion of relevant papers that considered each item, as follows: green – [75%, 100%]; yellow – [50%, 75%); orange – [25%, 50%); and red – [0%, 25%), thereby indicating which categories have received high levels of coverage (i.e. green), which have received reasonable levels of coverage (i.e. yellow), which have received relatively low coverage (i.e. orange) and which have received poor levels of coverage (i.e. red).

5. Discussion

In this discussion, the degree to which the questions that were raised in Section 2 are addressed by the DSSs are discussed based on the results of the review presented in Section 4.

5.1. Case study locations, purposes and level of management targeted by NHRR DSSs

DSSs have been applied most extensively across Europe and North America, with growing attention within South East Asia (see Fig. 15). In contrast, there were no case study locations in Africa, and only one in South America, amongst the reviewed papers. This is

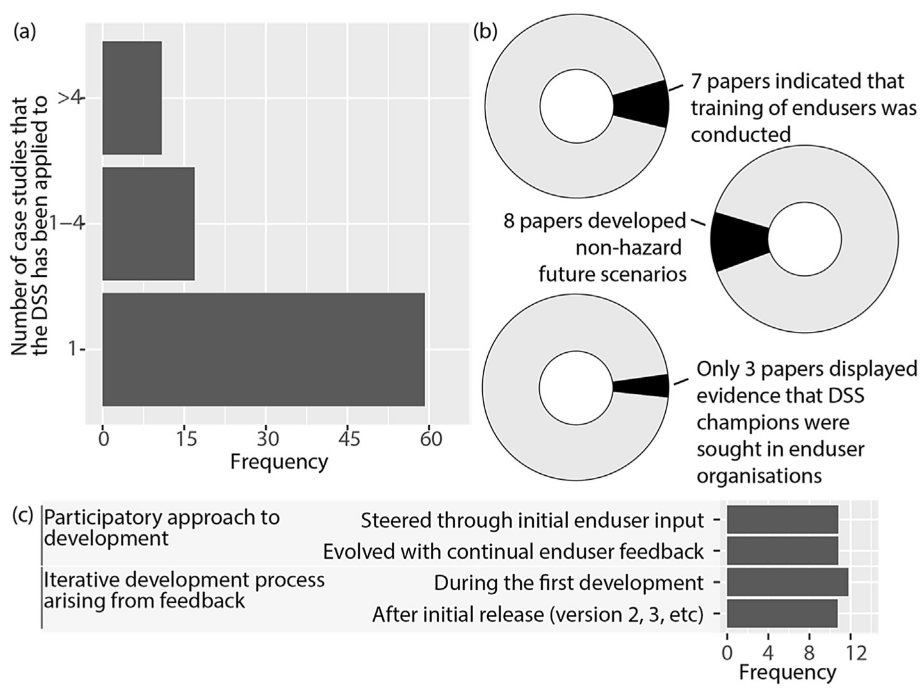

Fig. 26. (a) Number of case studies in which DSSs have been used as evidenced in the papers under review; (b) Proportion of papers reviewed that indicated that (i) training was conducted, (ii) non-hazard scenarios were developed, and (iii) that DSS champions were sought; (c) end-user engagement in development.

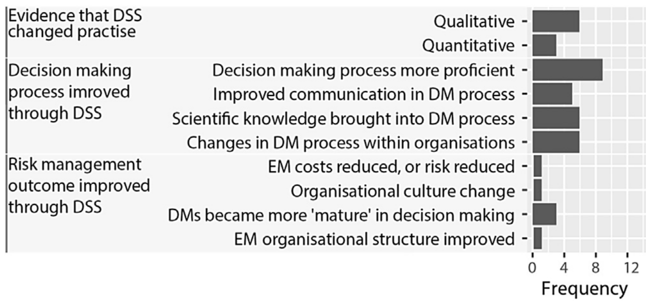

Fig. 27. Frequency of papers reporting on each of the subcategories in the monitoring and evaluation section of the taxonomy. Acronyms are: emergency management (EM); and decision makers (DM).

despite the relatively high vulnerability and hazard level that exists in these continents, as shown in Fig. 15. Therefore, stronger collaboration with African and South American researchers and institutions could yield beneficial outcomes for risk management in these countries.

The purpose of the DSSs in the review tended to be on lower-level decision support, as was discussed in Section 4.1.1: the visualisation of where hazards occurred, the estimation of losses (predominantly direct, see Section 4.2.2) from hazard events, in addition to testing the expected performance of risk-reduction measures. Similar with other surveys of DSSs more generally (Eom and Kim, 2005; Eom et al., 1998), the results of this review show that there has been less focus on DSSs providing higher levels of decision support that could significantly assist with the development of risk-reduction plans or strategic policy development —DSSs that could suggest and analyse mitigation alternatives or provide greater rigour to assessments through uncertainty/sensitivity analysis. Decisions at higher levels of government are an important aspect for risk management not strongly supported across the reviewed DSSs, either. For example, treasury/finance departments could use DSSs to understand investment ratios between risk reduction and response and the level of financial reserves required for relief after disaster events occur. They could also be used for helping decide what level of financing is required across the different hazards, and between different government departments responsible for land planning, land management, and other government departments that have roles in risk management.

5.2. *Types of hazards considered and the state of multihazard assessments within DSSs*

The hazards that received most attention within the papers reviewed were flooding, wildfire, earthquake and coastal surge, with much less work on drymass and wetmass movements, storms, volcanoes and extreme heat/cold (see Section 4.1.2, Figs. 15 and 28). The fact that DSSs on flooding/coastal surge and earthquake featured prominently is unsurprising, given that of the total economic losses from natural hazards over the period 1900–2015, approximately 40% were due to flooding and about 25% were due to earthquake (Daniell et al., 2016b). However, the lack of DSSs focused on storms is somewhat surprising, given that these events were responsible for about 20% of economic losses from natural hazards over the above time period (Daniell et al., 2016b). Similarly, the relatively high representation of DSSs focussing on wildfire is also not in agreement with the relatively small losses (≈2%) associated with this hazard. Potential reasons for the relative over-representation of DSSs that are focused on wildfire include the relatively high number of papers from Australia and the US, countries in which wildfires are prominent; that bushfires losses occur more frequently, leading to greater risk perception; and that wildfire risk can be managed relatively effectively and that losses from wildfire generally have a large emotive value associated with them, due to the complete destruction of homes and livelihoods.

The results indicate that DSSs usually focussed on one hazard in isolation (see Section 4.1.2 and Fig. 28) and that papers that did consider multiple hazards did not account for the dependencies between them. However, hazards often display interdependency. For example, one hazard event can trigger or increase the probability of another. This is observed when earthquakes trigger landslides and tsunami, and that flooding and landslide events often follow wildfires. As another example, two hazard events can be triggered by the same source — forming compound events. This is observed when storm cells cause both flooding and storm surge. In addition, with respect to risk-reduction strategies, mitigating the risk of one hazard can increase the risk of another. For example, in land-use planning for urban development, there will often be a trade-off in exposure across different hazards depending on where urbanisation is stimulated (e.g. development on a floodplain, or on urban fringes with higher wildfire risk). Additionally, revegetating catchments for flood risk reduction may increase fire risk.

5.3. *Risk criteria that have been chosen, and how they have been calculated and presented*

The results show that most articles included in this review developed risk-based criteria, reflecting the general shift from a hazard-based to a risk-based approach, as this provides a more comprehensive analysis of the expected impacts of natural hazards and enables better comparison between hazards. These risk criteria tended to focus on economic indicators (see *Problem formulation: Criteria* box in Fig. 28), which often amounted to estimates of direct losses from building stock (see Fig. 19). However, other aspects of economic losses, such as aspects of critical infrastructure (e.g. communication networks) and impacts on primary productivity, were generally neglected from consideration (see Fig. 19). This is a significant limitation, as business interruption and other indirect costs, the costs of implementing mitigation, and the side effects of mitigation can be very significant (Daniell et al., 2015; Felbermayr and Gröschl, 2014; Hallegatte, 2008; Loayza et al., 2012; Morris et al., 2008; Noy, 2009). In addition, natural hazards can also bring benefits through stimulating parts of the economy. Consequently, it is important to consider the above factors when forming risk-reduction plans. Additionally, the breakdown of benefits and costs to different parties/groups will be important in many decision making contexts, yet only Lindell and Prater (2006) separated benefits/costs borne between public and private holders amongst the papers reviewed. Adding economic models (i.e. input-output or computable general equilibrium), such as those developed in Jonkman et al. (2008), Hallegatte (2008) and Okuyama (2004) to a DSS would help quantify many of these aspects (see also Meyer et al., 2013; Rose, 2004a, 2004b). Finally, another notable omission from the vast majority of papers reviewed was consideration of ways to compare future risks. In economic evaluation, this is usually done using discount rates, although only two of the papers reviewed used discounting (see Section 4.2.2 and Fig. 20).

The criteria most commonly used considered direct losses from natural hazards impacting populated urban regions, with a clear preference for relatively simple, quantifiable indicators (see Section 4.2.2). Other criteria, such as recreational value (Morehouse et al., 2010) or short term assistance to those in need (Manley and Kim, 2012), were used in DSSs with more niche applications, such as wildfire in uninhabited forested regions or building evacuation management plan development, respectively. The reason for not

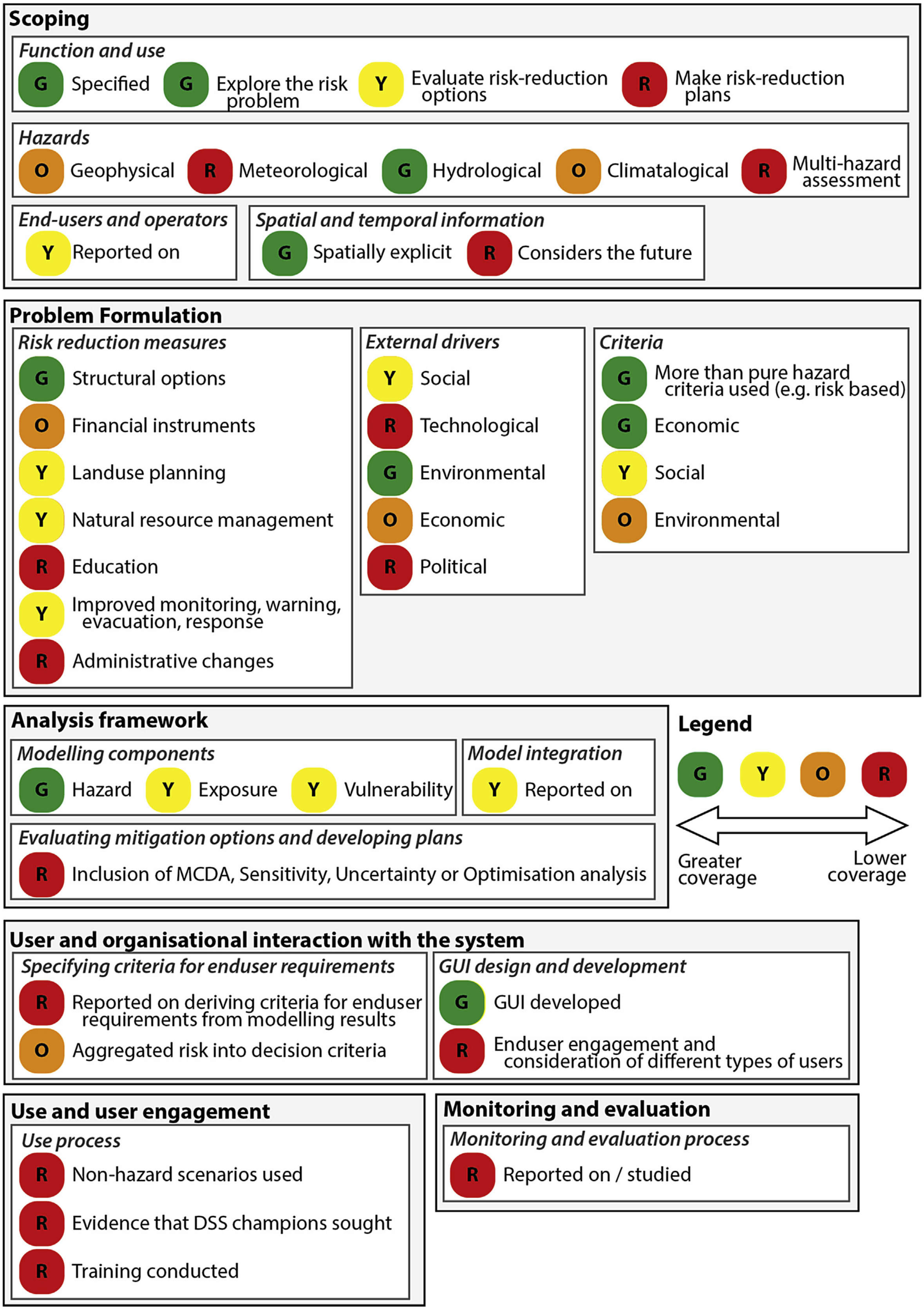

Fig. 28. Level of coverage for the reviewed categories, as surveyed across the reviewed articles. For the 'function and use' and 'hazard' categories within 'scoping', and for the 'problem formulation' categories, the coverage proportion was calculated relative to the subcategory with the highest frequency of use. The remainder of the coverage proportions were calculated relative to the number of DSSs tallied in the review.

developing a broader range of indicators for the majority of DSS applications often reflected a lack of necessity (e.g. for building evacuation management plans), or the difficulty in quantifying certain social, environmental and intrinsic criteria (Lindell and Prater, 2006), because data may not be available and/or there is insufficient process understanding to formulate a model for these criteria. This may explain why a number of criteria included in the proposed framework had very poor coverage across the reviewed articles — criteria such as loss to cultural values, public security, psychological impacts and political implications were largely not considered (see Fig. 19). While indicators for these impacts may be difficult to quantify, they are nonetheless very important when planning risk reduction, thereby presenting a clear research gap for future DSS development. For example, psychological impacts can have significant long-term effect, even long after physical rebuilding has been completed (Bland et al., 1996).

Almost all of the DSSs presented geographic maps displaying the spatial variation of losses or risks, particularly in regard to building stock (see Section 4.4.2 and Fig. 19). At the same time, there was some attention given to how decision criteria were chosen and derived, and whether they met end-user needs (Section 4.5 and Fig. 26). While maps of risk or losses are an important source of information for decision making, decision makers may require more resolved or summarised information (Meyer et al., 2013). For example, decision makers may want information that:

- presents an overall picture of risk that aggregates different types of criteria (e.g. environmental, social, economic) or disaggregates risk into specific aspects of a criterion (e.g. separate information for damage to buildings, transport and utility networks);
- presents risk for particular risk-owners (i.e. private, business, insurers, government);
- shows how specific risk types vary throughout time;
- compares risk across different administrative regions or vulnerable social groups; or
- categorises risk into specific classes (i.e. low, medium, high), rather than an annualised expected loss.

5.4. Time horizon of DSSs and consideration of future conditions

As was shown in Section 4.1.4, few DSSs had functionality for analysing future changes in risk, with most of these focussing on the long term (30 + years), which is understandable given the scale and planning required for many risk-reduction options, particularly large engineering works, as well as the timeframes involved in risk reduction via land use planning. When extended planning horizons were considered in the reviewed DSS papers, the drivers of change and future uncertainties that were incorporated into the analysis were limited. Most common was the inclusion of climate drivers on hazard (seventeen of the reviewed studies considered this, most commonly within the DSSs that included flood risk). However, the impact of climate change was never considered with regard to its impact and interactions with urban development and infrastructure (Hoornweg et al., 2011; Hunt and Watkiss, 2011) or how it can change social and network vulnerability (Chapman et al., 2013; Costello et al., 2009; Haines et al., 2006; Rübbelke and Vögele, 2011). Other drivers considered were mostly related to population changes, but there were some DSSs that also considered demographic changes on exposure and vulnerability, and economic development driving changes in exposure (Harrison et al., 2012; Mokrech et al., 2008, 2009).

The lack of DSSs focussing on future risks and risk-reduction planning is a key limitation, given the future uncertainty associated with the drivers for natural hazard risk. Apart from the impact of climate change on many natural hazards, increasing economic development, urbanisation, population growth and changing demographics and vulnerabilities are significant long term drivers for risk that should be incorporated more within risk modelling and risk-reduction planning. Consequently, the lack of consideration of uncertainties in these key drivers is likely to result in an underestimation of risk. As a result, there is a need for risk modelling to shift to a more dynamic characterisation of these drivers to more accurately capture changing risk profiles, to understand the implications of decisions made now on future risk, the scheduling of risk-reduction activity in the future, and to allow consideration of broader risk-reduction options reducing hazard, exposure or vulnerability (Brooks et al., 2005; Fraser et al., 2016; Highfield et al., 2014; Mitchell, 2003; Ranger et al., 2011).

5.5. Modelling strategies for various elements of risk (i.e. hazard, exposure, vulnerability)

Hazard modelling tended to use process based modelling frameworks (although for landslide, hazard models were empirical) and often used relatively complex models that focussed on specific events (see Section 4.3.1 and Fig. 21). Based on this observation, more research is needed to develop relatively fast-running models (in computational time) that develop probabilistic maps of risk variables (Ward et al., 2011). There is strong benefit in implementing fast-running models, so that DSSs can be used 'live' in workshop settings, and so that it is feasible to explore a large number of potential risk-reduction options, where formal optimisation strategies can even be used for this task. In addition, risk is often calculated across multiple events, using techniques such Monte Carlo simulation, which requires thousands of model simulations, giving further impetus to the use of fast-running models. A movement towards GPU modelling to facilitate a faster speed of multiple runs for personal computer use is currently occurring (Arca et al., 2015; Kalyanapu et al., 2011, 2012; Schaefer et al., 2015; Vacondio et al., 2014), however, this was not observed in any of the reviewed papers.

Alternatively, it may be possible to develop data driven models that estimate risk maps without simulating multiple events separately. For example, models following this paradigm have already been developed for wildfire risk using empirical expressions for quantifying fire behaviour, suppression capability and ignition potential (Atkinson et al., 2010). Similarly, there has been some work for similar empirical approaches in flood risk modelling (Van Dyck and Willems, 2013). Data driven models tend to be faster running, and if probabilistic maps can be produced without computationally expensive procedures, such as Monte Carlo simulation, the benefit is even greater in terms of running time.

As to be expected, a number of different software and development environments were used for implementing the DSSs, including third generation programming languages (e.g. Fortran), fourth generation languages (e.g. Matlab and Python), GIS systems, combinations of existing models, and existing DSSs (see Section 4.4.2 and Table 2; also refer to de Kort and Booij, 2007). Despite the variability, GIS was the most prevalent platform for developing DSSs, most probably due to the fact that risk is inherently spatial, making the ability to display risk using geographical maps a distinct advantage. However, when implementing a system within an existing GIS, it was often not explicitly stated within the papers whether an analysis was conducted within a GIS, whether a tool or workflow was implemented using GIS functionality, or whether a complete GUI was built that was powered by a GIS backend or desktop. This can have a significant bearing on the ease with which the system can be used, how automated or guided the analyses may be, and the ease with which the system can be applied at other locations. This could generally not be assessed based on the level of detail provided in the papers.

Most of the modelling components within DSSs were developed in-house by the DSS developers, despite there being over 80 validated open source/open access software packages existing for modelling a broad array of hazards (Daniell et al., 2014). However, only nine of the DSSs included one of these models. Therefore, there is good opportunity to leverage existing models for more rapid development of DSSs, an opportunity that is not extensively taken in present DSS development.

5.6. How successfully have DSSs been deployed, and are they used for their intended purpose in practice?

DSSs should be intuitive to their end users, and display information of importance to them and relevant for the context of the DSS deployment. Only 13 papers stated end-user involvement in GUI design, and fewer with regard to end-user involvement in specifying decision criteria. Learnings from stakeholder involvement in the process of scoping and designing DSSs are of interest and value to the researcher community, and are worthy inclusions within the academic literature. In general, stronger interaction with end-users has been reported to increase the likelihood of adoption of DSSs in practise (McIntosh et al, 2011; Valls-Donderis et al., 2014; Van Meensel et al., 2012). Developers or researchers spending time in end user organisations, and formal participatory processes such as interviews, questionnaires and workshops are all techniques which could be employed to facilitate this, and some of these techniques have been successful in other DSS settings (van Delden et al., 2011a).

Only three of the DSSs mentioned the presence of dual interfaces for policy analysts and scientists. The level of control needed by both users of the software can differ significantly, and including all the controls the scientist may need for their work may make the system unintuitive for the policy advisor. Therefore, this is a significant gap in the literature, as previous experience has shown the value in dual interfaces (van Delden et al., 2011a).

Amongst the papers reviewed here, there was no study that reported on the success of natural hazard DSSs over the long or short term. Indeed, the success of DSSs with regard to environmental policy or management more generally has been infrequently addressed within the literature. There is great value in research budgets being allocated to monitoring the effect of DSSs once they have been implemented in end-user organisations — this is the ultimate success of a DSS and a significant research gap.

6. Summary and conclusions

In this paper, a systematic classification system for the review of NHRR DSSs has been proposed, where 101 papers (covering 77 different DSSs) were reviewed in accordance with this taxonomy. As summarised in Fig. 27, the degree of coverage of the different categories of the classification system was highly variable among the papers reviewed. Categories that received a high level of coverage (as indicated by a green traffic light), included articulation of the purpose of the DSS and the decision tasks that the DSS was capable of supporting. There was also good coverage of DSSs that were able to identify areas of risk, and the likely economic implications of hazard impacts, particularly on direct building losses. Despite the focus of the review on NHRR DSSs, the number of systems that were purposely designed to test mitigation options only received low coverage within the literature (indicated by a yellow traffic light). This is also reflected in the coverage of exposure and vulnerability models, which are needed to test the benefits of risk-reduction options on values-at-risk. Categories that received poor coverage (as reflected by a red traffic light) include the consideration of meteorological risks, and consideration of how risk would change into the future (albeit a small number of DSSs provided good coverage of climate change). In addition, few DSSs had functionality to help screen through risk-reduction options, in order to suggest good measures for implementation. Furthermore, there was poor coverage generally within the categories related to stakeholder participation in development and use of the system. Finally, few papers were able to report on the success of the DSS, as covered in the 'monitoring and evaluation' category.

These results clearly highlight research areas that require greater focus within the literature, include:

1. Engaging higher-levels of government and facilitation of more strategic decisions, such as budgetary decisions, departmental targets, and an inter-hazard comparison of effectiveness of risk-reduction investment.
2. The nature of interaction with end users during DSS development. This should coincide with more extensive reporting in the literature on how DSSs are integrated within end user risk-reduction planning processes, and how the DSS was able to provide end users with required information to inform them in these processes.
3. Characterising and incorporating interactions between different hazard types, holistically assessing consequences of risk-reduction options on all hazard risks, and improving the representation of hazard-defence failure chains to better account for the frequency and severity of hazard events (Leonard et al., 2014).
4. The development and inclusion of exposure modelling to better account for the dynamics of exposure at a number of different time scales (i.e. daily, seasonal, long-term) and more sophisticated inclusion of risk-reduction measures, such as landuse planning, and improved warning and evacuation systems. This could be achieved, for example, through land-use models (Beckers et al., 2013; Klijn et al., 2012; Poussin et al., 2012; te Linde et al., 2011) and agent based models (Chen et al., 2006; Dawson et al., 2011);
5. Tightening the integration of hazard, exposure and vulnerability models, with diversification in the external drivers included, for richer representation of the dynamics and uncertainty in risk profiles.
6. Developing criteria for aggregating and/or comparing risk across different hazards, values-at-risk, future pathways, and spatial variability. It is often difficult to develop comparable risk based metrics across these aspects of natural hazard risk, even for the same criterion, given differences in the causal processes that result in loss.
7. Facilitating and encouraging future scenario analysis within NHRR DSSs that also include non-hazard trends that potentially affect risk significantly. This is critical, given the high degree of uncertainty and complexity in understanding and reducing natural hazard risk, especially in the long-term, due to the complex interaction within social-environmental systems that leads to risk. Plausible future scenarios (Maier et al., 2016) have been applied to a wide range of fields including defence (Brown, 1968; Kahn and Wiener, 1967), business (Bradfield et al., 2005; Schwartz, 1996; Wack, 1985), environmental change (O'Neill et al., 2014; Reed et al., 2013; Rounsevell and Metzger, 2010), and technological change (Kuhlmann, 2001; McDowall and Eames, 2006; Misuraca et al., 2012). Familiarity with these applications are helpful for developing coherent and consistent (Moss et al., 2010) scenarios for use in natural hazard risk

management, facilitating consideration of the impact of current decisions on future risk (Fraser et al., 2016).

8. Including more sophisticated decision making tools within NHRR DSSs, especially for the identification of best performing risk-reduction portfolios and for more in depth understanding of the performance of risk-reduction options. This could be achieved through incorporating optimisation techniques (Arca et al., 2015; Maier et al., 2014; Woodward et al., 2014), sensitivity/uncertainty analysis (Ganji et al., 2016; Norton, 2015; Pianosi et al., 2016; Razavi and Gupta, 2015) (Ganji et al., 2016; Norton, 2015; Pianosi et al., 2016; Razavi and Gupta, 2015) and multi-criteria decision analysis (Zagonari and Rossi, 2013).
9. Reporting on the monitoring and evaluation of DSSs. The literature reveals very little about long-term adoption of DSSs and their effects on organisational efficiency and risk-reduction outcomes. It is considered that funding models for DSS development need to be improved, with greater allocation for implementation and monitoring.

As stated in the Introduction, the impacts of natural hazards are likely to increase significantly in the future, causing potentially devastating impacts to people, infrastructure and the economy. Disaster risk reduction will therefore play an increasingly important role in the future, making the development of DSSs that can assist with the process vitally important. Consequently, the findings of this review are extremely timely in terms of identifying gaps in existing knowledge and potential research directions that will enable DSSs to be developed that are better suited to assisting with meeting the increasing challenge of reducing natural hazard risk into the future.

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Appendix A. Methodology for selection of papers

As stated in Section 3 (Selection of papers for Review), a search query was developed containing keywords pertaining to DSSs, natural hazards, and risk-reduction. Results were sorted by relevance (where papers are ranked according to the number of search terms found within their title, abstract and keywords), and were then chosen by manually sifting through the search results, based on the subject matter of the paper, and the impact of the journal in which it was published. The subject matter of a paper needed to match the aims of this review.

To be included within this review, papers were required to be relevant for natural hazard risk reduction. This was based on their ability to test risk-reduction options or explicit claim by the authors of the paper being assessed. Individual risk-reduction options could be projects, policies or processes. These measures were also required to be strategic, rather than operational. For example, papers that considered the construction of reservoirs to reduce flood losses were included, but the development of release plans for reservoirs on a yearly or seasonal basis were excluded. Similarly, papers that considered the choice of when to evacuate was considered an operational decision, while the planning of evacuation routes and locating evacuation centres pre-hazard was considered a strategic decision. With regard to DSSs, papers that included systems, models or studies that had utility in making risk-reduction plans were included. It is noted that risk assessments are virtually always done to inform decision making – thus any article presenting a risk assessment software or system was included provided it met the other conditions.

Papers also were required to be published in journals of sufficiently high impact. The impact of a journal was assessed using Scopus' Impact per Paper (IPP) and Source Normalised Impact per Paper (SNIP). In general, either of these metrics were required to be above 1 for a journal to be included, however, there was some leeway in this assessment. A highly relevant paper was included even if the journal did not quite make this threshold.

Appendix B. Summary of papers included in review

Based on the process outlined in Section 2 and Appendix A, 101 papers were selected for review, a summary of which is given in Table B1.

Table B1
Details of papers reviewed.

Paper (and name of DSS, if applicable)	Location of application (and availability, if known)	Hazard (see Section 2.1.4)	Type of paper (see Section 3 for definitions)
Ahmad and Simonovic (2001) (Intelligent Flood Management System – IFMS)	Red River Basin, Manitoba, Canada	Fluvial flooding	Integrated software system
Ahmad and Simonovic (2006); Ahmad and Simonovic (2013) (Decision Support for Management of Floods)	Cedar Hollow, London, Ontario, Canada	Pluvial Flooding	Integrated software system
Akay et al. (2012)	Kahramanmaras Forestry Regional Directorate in Turkey	Wildfire	Case studies
Alçada-Almeida et al. (2009) (SIGUrb)	City of Coimbra, Portugal (http://www.d ec.uc.pt/sigurb/SI/si.htm)	Urban Fire	Technique for decision support
Aleskerov et al. (2005) (DSS-DM)	Besiktas municipality, Turkey	Earthquake	Integrated software system
Alonso-Betanzos et al. (2003) (Fire Risk Predictor System; Expert System for Forest Fire Management)	Galacia, Spain	Wildfire	Integrated software system
	Chania, Crete, Greece	Earthquake	Integrated software system

(continued on next page)

Table B1 (*continued*)

Paper (and name of DSS, if applicable)	Location of application (and availability, if known)	Hazard (see Section 2.1.4)	Type of paper (see Section 3 for definitions)
Anagnostopoulos et al. (2008) (SEISMOCARE)			
Aretano et al. (2015)	Torre Guaceto, Italy	Wildfire	Technique for decision support
Assilzadeh et al. (2010) (Landslide Monitoring and Management System)	Penang Island, Straits of Malacca, Malaysia	Wetmass movement	Integrated software system
Baird et al. (1994) (Land Use Planning and Information System – LUPIS)	Nadgee Nature Reserve, NSW, Australia	Wildfire	Integrated software system
Balsells et al. (2013)	New Orleans, Florida, USA and Rotterdam, The Netherlands	Pluvial Flooding	Technique for decision support
Bernknopf et al. (2006) (Land Use Portfolio Modeler – LUPM)	A Californian coastal community, Watsonville, USA (Freeware; https://geography.wr.usgs.gov/science/lupm.html)	Earthquake	Integrated software system
Bonazountas et al. (2007) (FOMFIS)	Island of Evoia, Greece	Wildfire	Integrated software system
Campos Costa et al. (2009) (LNECloss)	Lisbon, Portugal	Earthquake	Integrated software system
Castillo Soto (2012)	Región de Valparaíso, Chile	Wildfire	Technique for decision support
Ceccato et al. (2011) (DPSIR FRAME)	Two catchments in the Upper Danube - the Lech river basin, and Salzuch RB in Austria and Germany, respectively; and three catchments in the Brahaputra river - the Assam State of India, the Wang Chu river basin in Bhutan and the Lhasa river basin in Tibet	Fluvial flooding	Technique for decision support
Chang et al. (2010)	Nantou, Taiwan	Landslide	Technique for decision support
Chen et al. (2004)	Mount Macedon, Victoria	Wildfire	Technique for decision support
Clark et al. (2009)	Silas Little Experimental Forest, Pennsylvania, USA	Wildfire	Technique for decision support
Damiano et al. (2012)	Cervinara area, Italy	Wetmass movement	Technique for decision support
Dawson et al. (2009); Mokrech et al. (2011) (The Tyndall Coastal Simulator)	Tyndall Coast, England	Coastal flooding, Fluvial flooding	Integrated software system
de Kok et al. (2008) (Elbe DSS)	Elbe River basin, Germany (Closed-source, non-free; http://riks.nl/projects/Elbe-DSS; http://elise.bafg.de/?3283)	Fluvial flooding	Integrated software system
de Kort and Booij (2007) (FLOod COontrol Decision Support – FLOCODS)	Red River in Vietnam and China	Fluvial flooding	Case studies
Elnashai et al. (2008a); Elnashai et al. (2008b) (MAEviz – HAZTURK)	Istanbul, Turkey	Earthquake	Integrated software system
Ford and Killen (1995) (Trinity River Advanced Computing Environment – TRACE)	Trinity River Basin, Texas, USA	Fluvial flooding	Integrated software system
Gärtner et al. (2008)	Late successional reserves in Washington and Oregon, East of the Crest of the Cascade Mountain Range, USA	Wildfire	Technique for decision support
Gumusay and Sahin (2009) (Wildfire Management System)	Area around Mt. Babadağ, Turkey	Wildfire	Integrated software system
Haas et al. (2013)	USA	Wildfire	Technique for decision support
Haldar et al. (2013) (Seismic Vulnerability and risk assessment – SeisVARA)	Dehradun, India (Open source)	Earthquake	Integrated software system
Hancilar et al. (2010) (ELER)	Istanbul, Turkey (Open source; http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1_6_176.depmuh)	Earthquake	Integrated software system
Harrison et al. (2012) CLIMSAVE	Europe, Scotland (Accessible to public; http://www.climsave.eu/climsave/index.html)	Fluvial flooding	Integrated software system
Haynes et al. (2008)	Edinburgh, Scotland	Fluvial flooding	Technique of decision support
Hinkel and Klein (2009); Vafeidis et al. (2008) (Dynamic and Interactive Vulnerability Assessment – DIVA)	Global (Freeware; http://www.diva-model.net)	Coastal flooding	Integrated software system
Henriques et al. (2008); Holman et al. (2008a); Holman et al. (2008b); Mokrech et al. (2009); Mokrech et al. (2008) (Regional Impact Simulator)	North-West England, East Anglia	Coastal flooding, Fluvial flooding	Integrated software system
		Fluvial flooding	Integrated software system

Table B1 (*continued*)

Paper (and name of DSS, if applicable)	Location of application (and availability, if known)	Hazard (see Section 2.1.4)	Type of paper (see Section 3 for definitions)
Hübner et al. (2009); Ostrowski et al. (2003) (nofdp IDSS)	Muemling River, Germany Breda, The Netherlands (Open source; http://nofdpidss.sourceforge.net)		
Iliadis (2005) (FFIREDESSYS)	Greek Prefectures	Wildfire	Integrated software system
Kalabokidis et al. (2016) (AEGIS)	Kalamanta, Mousoures, Kamiros, Pithagorio, Anthemountas, Ag. Triada, Mandra, Greece (Freeware; http://aegis.aegean.gr/?lang=en)	Wildfire	Integrated software system
Kalabokidis et al. (2011) (AUTO-HAZARD PRO DSS – AHP)	Lesvos Island, Greece	Wildfire	Integrated software system
Kaloudis et al. (2005) (Wildfire Destruction Danger Index DSS – WFDDI-DSS)	None specified	Wildfire	Integrated software system
Kaloudis et al. (2008) (Wildfire Risk Reduction DSS – WRR-DSS)	*Pinus halepensis* Mil. forest, North of Evia Island, Greece	Wildfire	Integrated software system
Karaman et al. (2008a); Karaman et al. (2008b) (Maeviz-Instanbul HAZTURK)	Istanbul, Turkey (MAEViz is open source; http://mae.cee.illinois.edu/software/software_maeviz.html; Development continuing under the Ergo consortium; http://ergo.ncsa.illinois.edu)	Earthquake	Integrated software system
Karmakar et al. (2010) (Flood Information System)	Upper Thames watershed, South-Western Ontario, Canada	Fluvial flooding	Integrated software system
Kim et al. (2011)	Kaki River, Nagaoka River, Niigata, Japan	Fluvial flooding	Technique for decision support
Kircher et al. (2006); Scawthorn et al. (2006); Schneider and Schauer (2006); Vickery et al. (2006) (HAZUS)	Many locations, U.S.A. (Freeware; https://www.fema.gov/hazus; https://msc.fema.gov/portal/resources/hazus)	Fluvial flooding, Hurricane, Earthquake	Integrated software system
Lemarié and Honnorat (2010) (Coupled Multi-Scale Downscaling Climate System)	East coast of South America, Uruguay	Coastal flooding	Integrated software system
Levy (2005) (SuperDecisions)	Yangtze River, Japan	Fluvial flooding	Technique for decision support
Lindell and Prater (2006) (Evacuation management decision support system – EMDSS)	None specified	Cyclone	Integrated software system
Lu et al. (2007)	Nantou County, Central Taiwan	Wetmass movement	Technique for decision support
Manley and Kim (2012) (exitus)	Human Services Research Centre, a building at the Utah State University Campus, USA	Hazard neutral	Integrated software system
Marchand et al. (2009)	Banda Aceh, Indonesia	Coastal flooding, tsunami	Case studies
Marulanda et al. (2013) (Comprehensive Approach to Probabilistic Risk Assessment – CAPRA)	Barcelona, Spain (multiple other applications noted in paper) (Open Source; http://ecapra.org)	Earthquake	Integrated software system
Mavsar et al. (2013) (Level of Protection Analysis System – LEOPARDS; KITRAL; SINAMI; US Fire Program Analysis – FPA)	None specified (US FPA: https://www.fpa.nifc.gov)	Wildfire	Review article - DSS Software
Melo et al. (2014)	Agualva, Portugal	Pluvial flooding	Integrated software system
Molina et al. (2010) (Seismic Loss Estimation using a Logic Tree Approach - SELENA)	Oslo, Norway (Open source; http://selena.sourceforge.net/selena.shtml)	Earthquake	Integrated software system
Morehouse et al. (2010) (Fire-Climate-Society – FCS-1)	Jamez Mountains, New Mexico; Chiricahuas, Arizona; Catalinas-Rincons, Arizona; Huachucas, Arizona, USA	Wildfire	Technique for decision support
Nauta et al. (2003) (Laguna Lake Development Authority – LLDA DSS)	Laguna de Bay, Philippines	Coastal flooding	Integrated software system
Noonan-Wright et al. (2011) (Wildland Fire Decision Support System)	USA http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml	Wildfire	Integrated software system
Pagani et al. (2014); Silva et al. (2013) (OpenQuake)	Global model (applied to an Indonesian case study) (Open source; https://www.globalquakemodel.org)	Earthquake	Integrated software system
Pagano et al. (2014)	Ofanto Aqueduct system, Italy	Multihazard: Earthquake, fluvial flooding, wet mass movement (landslide)	Technique for decision support

(*continued on next page*)

Table B1 (*continued*)

Paper (and name of DSS, if applicable)	Location of application (and availability, if known)	Hazard (see Section 2.1.4)	Type of paper (see Section 3 for definitions)
Pasi et al. (2015); Pranantyo et al. (2015) (InaSAFE)	Veneto, Italy; Padang, Maumere, Mount Slamet, Jakarta, Indonesia	Multihazard: Coastal flooding, earthquake, tsunami, volcano, river flooding	Integrated software system and Case study
Piatyszek and Karagiannis (2012)	None specified	Fluvial flooding	Technique for decision support
Qi and Altinakar (2011a, 2011b); Qi and Altinakar (2012)	Milledgeville, Georgia (Oconee River), USA	Fluvial flooding	Integrated software system
Rajabifard et al. (2015) (Intelligent Disaster Decision Support System – IDSS)	Maribyrnong river and Warrandyte, Victoria, Australia (http://www.cdmps.org.au/intelligent-disaster-decision-support-system-iddss/)	Fluvial flooding, Wildfire	Integrated software system
Rashed and Weeks (2003)	Los Angeles County, California	Earthquake	Integrated software system
Roca et al. (2006) (ESCENARIS; SES 2002)	Catalonia, Spain	Earthquake	Technique for decision support
Rodrigues et al. (2002) (DamAid)	Funcho-Arade System in Algarve, Southern Portugal	Fluvial flooding	Integrated software system
Rodríguez et al. (2011) (System for Evaluation and Diagnosis of Disasters – SEDD)	Global	Multihazard	Technique for decision support
Schielen and Gijsbers, 2003 (DSS-large rivers)	Large River systems in the Netherlands (Rhine and Meusse)	Fluvial flooding	Integrated software system
Schmidt et al. (2011) (RiskScape)	Various locations New Zealand (Closed source; https://www.riskscape.org.nz)	Earthquake, volcano, flooding, storm, tsunami	Integrated software system
Shang et al. (2012)	Mark Twain National Forest, Eleven Point Unit (Current River Hills Subsection), Missouri, USA	Wildfire	Technique for decision support
Sinha et al. (2008) (Risk.iitb)	Mumbai, India	Earthquake	Integrated software system
Strunz et al. (2011) (German Indonesian Tsunami Early Warning System DSS – GITEWS)	Southern Sumatra, Java and Bali, Indonesia (http://www.gitews.org)	Coastal flooding, tsunami	Case studies
Thompson et al. (2015) (FireNVC)	USDA's Rocky Mountains region including most parts of Colorado, Kansas, Nebraska, South Dakota, Wyoming, USA	Wildfire	Integrated software system
Thumerer et al. (2000)	East Anglia, England	Coastal flooding	Integrated software system
Torresan et al. (2016); Torresan et al. (2010) (Decision Support System for Coastal Climate Change Impact Assessment – DESYCO)	Bari, Esino River Basin, Italy, Zurich, Switzerland, Tunisia, Mauritius Northern Adriatic Sea and the coast of the Veneto and Friuli Venezia Giulia regions (Open source; https://www.cmcc.it/models/desyco)	Coastal flooding, Pluvial flooding, River flooding	Integrated software system
Toutant et al. (2011) (SUPREME)	Province of Quebec, Canada (Open Source)	Heatwave	Integrated software system
Tralli et al. (2005)	None specified	Multihazard: Earthquake, Volcano, fluvial and coastal flooding, wetmass movement	Technique for decision support
Vacik and Lexer (2001)	Vienna, Austria	Wetmass, drymass movement	Integrated software system
Vafaei and Harati (2010)	South West Iran	Coastal flooding	Integrated software system
Van Damme et al. (2003)	Boreal plain forests, 120 km NW of Edmonton, Alberta, Canada	Wildfire	Integrated software system
van Dongeren et al. (2014) RISK-KIT	Kristianstad, Sweden; Kiel Fjord, Germany; North Norfolk, UK; Zeebrugge, Belgium; La Faute sur Mer, France; Bocca di Magre, Italy; Porto Garibaldi, Italy; Varna, Bulgaria; Ris Formose, Portugal; (www.risckit.eu)	Coastal flooding	Integrated software system
Wan (2009); Wan and Lei (2009); Wan et al. (2008)	Chen Yu Lan River area, (Lei-Pa National Park), Nantou, Taiwan	Wetmass movement	Technique for decision support
Wang et al. (2013) (OSIRIS)	Yunlin County, P. R. China	Fluvial flooding, land subsidence (slow onset)	Case studies
Woodward et al. (2014)	A section of the Thames Estuary, England	Fluvial flooding	Technique for decision support
Wybo (1998) (Fire Management Information System – FMIS)	None specified	Wildfire	Integrated software system
Xu et al. (2007)	The Dutch section of the Meuse River	Fluvial flooding	Technique for designing DSSs
Yadollahi and Zin (2012)	None specified	Earthquake	Integrated software system
Yang et al. (2011) (Landscape Ecological Decision and Evaluation Support System Model – LEDESS)	Yunlin County, Taiwan	Fluvial flooding	Integrated software system
Ye (2014)	None specified	Snowstorm	Technique for decision support
Yu et al. (2014)		Riverine Flood	Integrated software system

Table B1 (*continued*)

Paper (and name of DSS, if applicable)	Location of application (and availability, if known)	Hazard (see Section 2.1.4)	Type of paper (see Section 3 for definitions)
	Tsengwen River basin, Chianan Irrigation area, 6th district of Taiwan Water Corporation		
Zagonari and Rossi (2013) (Heterogeneous Multi-Criteria Multi-Expert Decision-Making MC-ME-DM)	Cesanatico, Italy	Coastal flooding	Technique for decision support
Zaidi and Pelling (2013)	London, UK	Heatwave	Review article - DSS Software
Zanuttigh (2011); Zanuttigh et al. (2014) (Innovative coastal technologies for safer European coasts in a changing climate DSS – THESEUS)	Cesanatico, Po delta and adjoining coast, Italy, Elbe estuary, Germany, Varna Spit, Bulgaria, Santander spit, Spain, Gironde estuary, France, Plymouth sound to Exe estuary, United Kingdom, Scheldt estuary, Belgium. (Freeware for scientific non-commercial research activities; http://www.theseusproject.eu/dss)	Coastal flooding	Integrated software system

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