



Decision Support

System-focused risk identification and assessment for disaster preparedness: Dynamic threat analysis

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ARTICLE INFO

Article history:

Received 20 December 2014

Accepted 20 April 2016

Available online 27 April 2016

Keywords:

(P) Risk analysis

(P) Risk management

OR in disaster relief

Critical human activity systems

Qualitative system dynamics

ABSTRACT

Current approaches to risk management stress the need for dynamic (i.e. continuous, ongoing) approaches to risk identification as part of a planned resource application aimed at reducing the expected consequences of undesired outcomes for the object of the assessment. We contend that these approaches place insufficient emphasis on the system knowledge available to the assessor, particularly in respect of three factors, namely the dynamic behavior of the system under threat, the role of human agents and the knowledge availability to those agents.

In this paper we address the first of these shortcomings, namely the mobilization of explicit system knowledge in the identification of risks. We present a procedure for mobilizing quantitative and qualitative dynamic system knowledge using the case of flood threat to an electricity substation as a worked example. We assert that the approach described offers the potential of improving risk cognition by mobilizing system knowledge.

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1. Introduction

This paper is about the identification and assessment of system risk, which is an early and important part of the process of mitigation and control of those risks under conditions of limited resource availability. We are concerned primarily with safety and mission critical systems whose behavior is commonly conditioned by the decisions and actions of human agents who form an inextricable part of the system assets. We refer to this class of systems as critical human activity systems, henceforth CHASs (vide [Checkland, 1981](#)). The example we use towards the end of the paper to illustrate our approach is that of the response to threats to electricity supply of a flood-threatened electricity sub-station.

We observe four shortcomings in current approaches, namely (1) insufficient mobilization of the inherent dynamics of the system, leading to an unnecessarily narrow cognition of risks; (2) lack of attention to the human agency involved; (3) similarly to the role of knowledge gaps and (4) issues of multiple definition by stakeholders, known as plurality.

We are concerned here with addressing the first of these, offering a workable, dynamic, system-based risk identification methodology upon which further work can extend to include treatment of

(2) to (4) above. We base our methodology on a qualitative modeling approach in order to include the widest spread of available knowledge about the system, much of which is, by its nature, non-numerical. The subsequent use of numerical data is not precluded, however, since the qualitative approach also provides a method of identifying which numerical sources should be accessed by further, focused study, such as simulation.

After a brief examination of the shortcomings of existing approaches, we describe the characteristics of the methodology, applying it to the particular case of the flooding risk to a component of the electrical distribution system, namely a distribution sub-station located near the coast.

2. Shortcomings of existing approaches

2.1. General approach to CHASs

We draw the following observations about existing approaches to CHAS risk assessment. First, there is a tendency towards the use of taxonomic and objective-based risk assessment ([AIRMIC, Alarm, & IRM, 2010](#); [Borodzicz, 2005](#); [Dorfman, 2007](#); [Trickey, 2011](#)). While such approaches implicate the internal behavioral characteristics of the object under assessment (the system behavior), there is little evidence of this important source of risk knowledge being mobilized explicitly. There is thus a tendency both in academic literature and in practice to interpret the term 'dynamic'

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[as in “dynamic risk assessment”] as being to do with the extent to which the risk assessment is performed - on a continuing basis, as opposed to a once-for-all snapshot (Adams, 1995; van Nederpelt, 2012). For example, the UK’s Fire Service Inspectorate defines dynamic risk assessment within the bounds of an ongoing incident as “*the continuous assessment of risk in the rapidly changing circumstances of an operational incident, in order to implement the control measures necessary to ensure an acceptable level of safety*” (HM Fire Service Inspectorate, 1998). This approach is, of course, strongly to be preferred over any static or even episodic approach (Borodzic, 2005; Gorrod, 2004) but our use of the term ‘dynamic’ here connotes the additional attribute that knowledge of the likely dynamics of the system and the causal mechanisms for those dynamics give clues to the precursors of risk events deriving both from within the system and from outside it (Fuchs, Keiler, Sokratov, & Shnyarkov, 2013). In short, if we mobilize knowledge of why the system behaves as it does, we have a better chance of perceiving the origins of risk events originating both from within the system or from its immediate environment.

Second, although in a significant class of systems (safety or mission critical systems) the role of humans is frequently critical, we observe little in the way of structured analysis of the role of human agents in the operation of the assessed system (Hopkin, 2012).

Third, particularly in the case of CHASS, there is little analysis of the role of knowledge in the interaction of the human agents with the system under assessment (Hillson & Murray-Webster, 2007).

Fourth, it is not clear from the existing literature whether sufficient emphasis is given in risk identification and assessment to the plural nature of the valuation of risk outcomes, by which we mean the different valuations placed by different stakeholders on system outcomes (Checkland & Scholes, 1990; Clarke, 2001).

2.2. OR and disaster management

The management of disasters and particularly flood events, as an important subset of CHASS has been of interest to the OR community for some time, in the form of disaster operations management (DOM), and by inclusion emergency planning. Disaster operations represent the set of activities performed before, during and after a sudden, devastating incidence that seriously disturbs the functioning of a population and causes human, material, economic or environmental damages that are beyond the ability of the affected population to cope with by using its own resources. Thus we consider it pertinent to also consider papers related to emergency operations research (EOR), the distinction being centered on whether an emergency requires a routine or more serious and spontaneous response. Essentially, EOR has not limited itself in the same way as DOM and includes all types of emergencies and not only those related to serious, spontaneous and disastrous events (Simpson & Hancock, 2009).

An examination of existing literature reveals that a hard OR approach (using for example, mathematical programming, simulation and statistical modeling) is the most commonly deployed approach for DOM, while ‘soft’ OR techniques, are predominantly qualitative in nature, remain underused despite their suitability to the domain (Galindo & Batta, 2013; Simpson & Hancock, 2009). Our literature review resulted in the identification of only one study that specifically applied a ‘soft’ OR approach to disaster planning (Gregory & Midgley, 2000). A modified version of SSM was employed with the aim of supporting the planning of a multi-agency counseling service that could be activated in the event of a disaster. Extending the scope of our search to include emergency planning resulted in the identification of a further three papers using soft OR. These include the use SSM for location planning of a new fire station (Hewitt, 2002) and SODA for improving knowledge management

Table 1

Studies that have applied hard OR methods in the context of DOM and EOR.

Hard OR method	Application context	Refs
Math programming	Evacuation planning under hurricane/flood conditions.	Sherali et al. (1991)
Probability and statistics	Anticipating catastrophes caused by rainfall.	Coles and Perrichi (2003)
Simulation	Decision support system for evacuation planning in Taiwan.	Han (1990)
Decision theory	Earthquake damage estimation & decision analysis for emergency shut-off of city gas networks.	Cret, Yamazaki, Nagata, and Katayama (1993)
Queuing theory	Planning of an emergency ambulance service.	Bell (1969)
Fuzzy sets	Optimal flood control.	Esogbue, Theologidu, and Guo (1992)
Stochastic programming	Transportation planning in disaster response.	Barbarosoglu and Arda (2004)

in the NHS to better plan and deliver patient care (Edwards, Hall, & Shaw, 2005).

Many of the activities performed under DOM, then, are addressed through the application of ‘hard’ OR methodologies. For example, the location of shelters in preparation for an evacuation or, indeed, the evacuation itself, may best be addressed through mathematical location and transportation analyses. Furthermore, given the uncertainty associated with variables such as the location and intensity of a disaster, these can be mapped well using statistics and probability models. Table 1 provides a summary.

The literature reveals, however, that despite the apparent suitability of the quantitative methods their impact on policymaking and practice has been relatively low (Walker, 1981). This is primarily the result of the lack of use of ‘soft’ OR approaches at the initial stages of a project to help structure and formulate problems that are by their nature dynamic, ill-defined and disorganized (Sherali, Carter, & Hobeika, 1991). An additional exacerbating factor is the presence of multiple policy makers (or system owners). One of the primary strengths of quantitative methods is the clarity with which they represent an agreed reality, but where there are multiple outcome valuations and even multiple understandings of reality, this singularity of representation becomes hindrance.

3. Definitions, general approach and scope of paper

3.1. Risk management process

Risk management in general usage (Morgan & Henrion, 1992; USEPA, 2004; IRM et al., 2002) refers to a process of **identification** and assessment of the **likelihood of occurrence** and **impact** of deleterious outcomes of an object in focus resulting from (potential) **risk events** which may or may not be reified in a particular circumstance (Alberts, Dorofee, & Marino, 2008; ISO/IEC, 2009; Stoneburner, Goguen, & Feringa, 2002). We shall refer to the object of this analysis as a system (NIOSH, 1998), since, for it to be worthy of consideration, it will be of a complexity and span of impact greater than a single, undifferentiated event. For example, one would refer to the effects analysis of a single flood event, a single, isolated, hydraulic phenomenon, rather than to its risk analysis. It is not the single flood itself which is the subject of risk analysis, but the effect of the flood on the environment and society in which it takes place as a particular embodiment of an underlying system of hydrological phenomena of which the particular flood is but a single example.

Risk management as a process, then, moves from identification and assessment to **control, mitigation and consequence** management (Moteff, 2005), seeking to accommodate inevitable resource limitations within an **action plan** (ISO/DIS, 2009) aimed at satisfying a set of outputs or consequences of the causative risk event (Stoneburner et al., 2002).

Risk identification and assessment are key steps within any risk management process, whether that takes place within supply chain management (Manui & Mentzer, 2008), construction projects (Sun, Fang, Wang, Dai, & Lv, 2008), banking and finance (Duca & Peltonen, 2013), or disaster risk reduction (Zaidi & Pelling, 2015). Risk identification and assessment were considered key priorities of the Hyogo Disaster Reduction Framework (ISDR, 2005), which forms the key focus of this paper. Following the International Standards, Risk Identification is defined as the “process of finding, recognizing and describing risks”, which involves “the identification of risk sources, events, their causes and their potential consequences” (ISO, 2009). Risk assessment is, then, the “overall process of risk identification, risk analysis, and risk evaluation”, making Risk Identification a component part of risk assessment. Alternatively, risk identification and risk assessment can be seen as sequential steps with the risk management process (McEntire, 2015).

The extensive US-based work sponsored by the US Department of Homeland Security (DHS) exemplifies this approach, with programs examining a wide variety of threats to the security of US citizens and assets (and by extension other developed countries). Topics include food protection (University of Minnesota), maritime security (Stevens Institute of Technology), terrorism (University of Maryland) coastal and critical infrastructure risk assessment (Universities of N Carolina and Illinois) (DHS, 2015). These studies (to the extent that they are publicly available) exhibit a high degree of sensitivity to the underlying dynamic mechanisms of the risks which they are attempting to elucidate, for example, in the 30 projects falling under the START initiative on responses to terrorism (Start, 2015). There is evidence that a holistic system approach similar to that advocated here would be resonant with and contributory to the ambitions of these programs to establish a complete risk identification their topic areas.

3.2. Connections with strategic analysis methods

There are striking resonances between the processes of strategic management under uncertainty, (and, in particular, the use of scenario planning to identify robust strategic responses) and of the risk management of a system. Both are concerned with the identification of action plans aimed at maximizing desired outputs under conditions of limited resources when there exists an uncertain trajectory of the system state over time. Scenario planning is a technique common to the two areas of management, and recent work (Powell, 2014) has shown the connection between scenario generation and the underlying dynamics of the system, the future behavior of which is being predicted. It is upon this underlying connection that this present work is based.

The outcome states of the system must be a consequence of the starting conditions together with the dynamic mechanisms in operation in the organization as affected by any exogenous inputs to the system. These latter can be included in the analysis either explicitly as external ‘disruptions’, an approach favored implicitly in much risk analysis (Alexander & Sheedy, 2005; Morgan & Henrion, 1992), or by extending the boundary definition of the system-in-focus, so as to include a sufficiently wide set of system mechanisms within the boundary of the system-in-focus as to allow the treatment of disruptions as dynamic mechanisms within that system. For example, in strategic work, the effect of a competitor’s pricing policy can be treated either as a disruption external to the system representing the firm or can be included as part of a wider

market model in which the firm sits (Howard, Vidgen, Powell, & Powell, 2007; Powell & Swart, 2010) Here we take a dual position, both extending the boundaries of the system under risk analysis to include threat mechanisms which can be predicted, and carrying out a vulnerability analysis of possible disruptions to the relevant dynamic system mechanisms.

3.3. Contribution and utility of the work

The merits of the method, then, can be summarized as follows.

- 1 **Identification of cross-functional risks** between subsystems of a CHAS (physical, social valuation and political) which are not apparent when viewed separately.
- 2 **Auditable completeness** in the risk analysis, in that each dynamic process is captured (and is agreed to have been captured) in the ID and an exhaustive examination of the effects of disruptions can then be carried out.
- 3 **Improved cognition of risks.**
- 4 **Connection of instigating, disruptive variable changes and system effects.**

The utility of the work lies in the ability of the system representation method used, namely Qualitative System Dynamics (QSD) (Coyle, 1996) to capture dynamic system mechanisms in such a way as to mobilize a wide range of informants’ knowledge and subsequently reveal underlying system mechanisms. The method identifies dynamic loops, resonant mechanisms which provide knowledge of the processes within the system.

In the following section we illustrate the QSD method with a model of the potential flooding of an electricity sub-station connected to the UK national distribution grid and protected both by a coffer arrangement (concrete or brick retaining enclosures aimed at preventing water ingress to the electrical transformers and switching installation) and by emergency pumps.

4. Modeling approach – Qualitative System Dynamics (QSD)

4.1. Disaster management analysis – role of qualitative methods

Although the terms ‘disaster management’ and ‘critical HASS’ are not synonymous, there is considerable overlap: almost all disasters are CHASS; almost all CHASS contain the seeds of disaster by virtue of their criticality. The key literature review on analytical techniques for disaster operations management (Altey & Green, 2006) includes natural, man-made and humanitarian disasters. Both it and the comparative work of Galindo and Batta (2013) show a strong predominance of quantitative modeling techniques for the purposes of disaster mitigation, preparedness, response and recovery. The proportion of qualitative studies that are identified as ‘Soft OR’ is less than 1 percent and that of ‘System Dynamics’ constitutes approx. 2 percent of studies.

Galindo and Batta identify a category called ‘Conceptual Analysis’ which accounts for 16 percent of all papers surveyed by them, the second largest category after ‘Math Programming’ (23 percent). Simpson and Hancock, (2009) report similar low levels of qualitative methods use. We argue that QSD provides for a structured approach for qualitative systems’ enquiry and that the application of this technique is particularly well suited for conceptual analysis in multi-stakeholder environments, as is the case with multi-agency planning around disaster operations (Gregory & Midgley, 2000).

A critical observation emerging from these reviews is that there is a dearth of applications of Soft OR. Such problem structuring methods offer opportunities for inclusive modeling approaches (e.g., through use of techniques like QSD and SSM in workshops with problem stakeholders and policy makers) thus improving the managerial product cognition, options identification, assessment

etc) from studies in emergency and disaster planning (Simpson & Hancock, 2009).

We recognize the existence of other qualitative approaches in the elicitation of risk through stakeholder participation, for example, through use of causal maps (Ackermann, Howick, Quigley, Walls, & Houghton, 2014), the use of SSM for the purposes of identifying the organizational stakeholders (Wang, Liu, & Mingers, 2015). For the purposes of risk identification in CHASs, however, we feel that the abilities of QSD to represent specific system dynamics and to mediate between the qualitative expression of these mechanisms and any possible quantitative representation (for example detailed simulation) are of particular importance.

QSD is a well-documented and extensively used technique (Coyle, 1996; Sterman, 2000). It originates from the mainstream of Systems Dynamics (hereafter SD) which deploys visual Influence Diagrams to structure numerical simulations. In its purely qualitative form (as used here), exploration of the system dynamics and behavior is not carried out through forcing departures from a quantitative reference mode, or baseline model but by direct appeal to the structure of the model. To the dedicated numerical modeler this may seem restrictive and arbitrary, but it has distinct advantages and practicalities.

Firstly, not all the variables of the simulation can be defined numerically, particularly as one moves from the representation of the laws of physics towards the social domain; it may be possible to define *water depth*, *velocity*¹, *probability of consumer supply loss* or even *cost of a flood in numerical terms*, but the human impacts, such as the *perceived risk to the community*, are less easily made numerical.

Secondly, examination of the structure of a model can produce, of itself, insight into those dynamic mechanisms which are significant in producing system output, since those mechanisms are adumbrated directly from the complex system representation which underwrites the simulation rather than indirectly by observation of system output. There is, of course, a disadvantage to this, in that the qualitative methods do not directly predict or illustrate system output as such, but where that disadvantage is material and (critically) where the simulation variables can be adequately represented numerically, the numerical simulation and the qualitative, structural analysis can be carried out in a complementary manner; they are not mutually exclusive.

The grammar of QSD diagrams is well known (Coyle, 1996; Eden, 1989; Sterman, 2000). The key components and characteristics are

- An influence diagram (ID) representing the causal links in the system, usually emerging from a facilitated focus group of informed persons.
- The descriptive variables should be well-defined and commonly understood by the informants
- Descriptive variables are linked by arrows representing causality (as distinct from mere correlation). Positive correlations are signified by a + sign attached to the arrow, negative correlations by a - sign. For the reader's convenience in diagrams, negative causal arrows are frequently shown dotted. For visual clarity, here arrows without signs are deemed positive.
- Analysis of an ID consists, in brief, of the visual inspection of the ID to extract key loops connecting variables, which represent key mechanisms of behavior within the system model of the ID.
- Manipulation of the connections within these causal loops forms the basis for action planning, bearing in mind that the behavior of each loop does not occur in isolation, there being

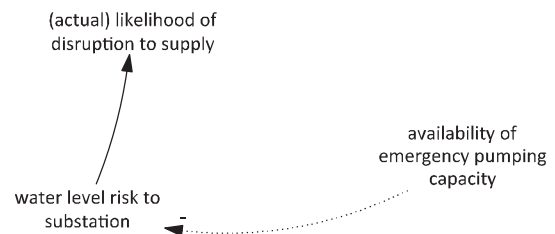


Fig. 1. Extract from electrical substation flood example.

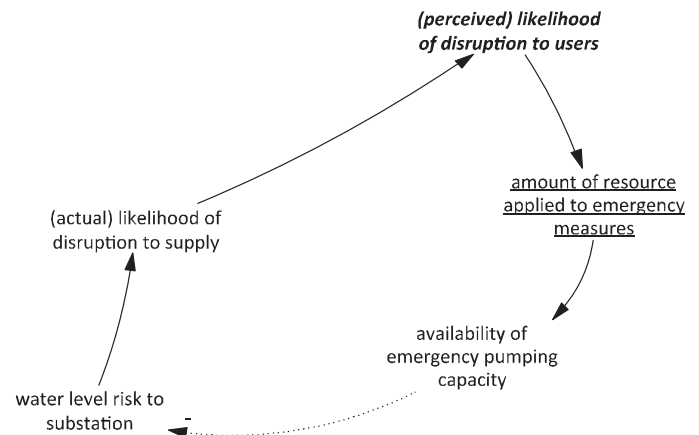


Fig. 2. Indicative example of a dynamic loop extracted from an ID.

interconnections between key dynamic mechanisms which collectively produce the system behavioral output.

Fig. 1 shows an extract from the full system model of the flood-prone electrical substation described more fully below.

Here we see a positive² causal link (in solid) indicating that if the *water level risk to substation* increases, the *(actual) likelihood of disruption to supply* will rise and that if the *availability of emergency pumping capacity* were to increase that *water level risk* would decrease (a negative sign on the arrow). In both cases other factors will bear upon the matter and the connections are neither linear, nor necessarily strong, in that further consideration may show that the link, while present, may be attenuated for reasons not at first evident.

The link between *availability of emergency pumping capacity* and *water level risk to substation* is shown dotted, since the polarity of the causal connection is negative, i.e. as the pumping capacity *increases*, the probability of *water level risk decreases*.

4.2. Analysis of IDs

The method of analysis of Influence Diagrams (IDs, sometimes called causal loop diagrams or CLDs) is well-documented (Coyle, 1996, Powell & Coyle, 2005) but is summarized here for convenience. It turns on the extraction from the ID of dynamic loops, closed cyclic structures of causality. These operate in concert to determine the system output under the effect of disruptions deriving from variables both on the boundary of and within the system. An ID can contain many hundreds, even thousands of loops, and so a combination of automatic loop identification using, for example, Vensim ©, and visual inspection is used to prioritize these for the subsequent identification of action aimed at manipulating their behavior towards the desired system output(s). Fig. 2 shows a simple example of a dynamic loop extracted from the full model.

¹ Descriptive variables which appear in models are represented in italic script, thus.

² Positive signs are suppressed in IDs in this paper for visual clarity.

The loop describes the connection between a perception of the likelihood of disruption to service and the consequential provision of emergency pump capacity to defend the substation from rising water levels.

Such loops are used to initiate consideration of actions aimed at manipulation of the overall system output, through the combined action of the loops towards a set of outcomes desired by the stakeholders. Loops are characterized by their speed and strength of effect on system outputs and the speed of their action. The loop shown in Fig. 2, on the assumption that stand-by resources are available (e.g. extra fixed or transportable pumping), will be quite quick in its action, whereas an allied mechanism which expresses the response of longer term investment on drainage infrastructure, for example, will be slower acting. The categorization of these mechanisms according to their strength of impact and the speed of application of that impact provides an important filtering mechanism by which potential actions can be prioritized.

The priority in general strategic management use of these methods is to identify interventions (beneficial disruptions) which, because of the resonance effects within the loops, have sustained effects. *Mutatis mutandis*, deleterious disruptions can cause continuing, even amplifying disbenefits, and examination of these undesired effects constitutes the equivalence of risk analysis at the strategic level, in that the identification of managerial action aimed at negating these effects reduces the risk of their disrupting the long term strategic implementation.

In risk identification however, as understood here, we are centrally concerned with the identification of the effects of disruptions *vis-à-vis* the 'steady state' strategic agenda. This requires an amendment to the analysis process deployed so as to concentrate upon the likelihood of disruptions to desired system behavior by changes in the input variables rather than focusing on sustained effect. A 'pulse' of disrupted supply to a local region due to transient but severe wind speed increases may not be strategic, since it will in time decay, but it is, nevertheless, the focus for the operational risk management and mitigation of the supply network of which our substation forms a part.

The risk identification process, then, can be summarized as follows.

- a. Construction of an Influence Diagram (ID), usually by a focus group of experts, covering the required span of managerial interest.
- b. Identification of those variables in the ID which have the capacity to act as disruptors of the system performance
- c. Examination of the dynamic processes in the ID, represented by the loops (vide Fig. 2)
- d. Identification of the effects of disruptions to those mechanisms
- e. Expression of the risks identified thereby.

In risk identification, where there is a need to full coverage of potential risks, we inspect, arrow by arrow, the causal mechanisms which underwrite the loop performance under disruption, enquiring at each step what the threats and response might credibly be. This has to be done by consideration of each of the important loops, since the risks emerging from consideration of an arrow in one loop may well be different from the risks identified in another mechanism. While this is onerous (a diagram may contain many hundreds of loops) the effort involved is a function of the need for completeness in the risk survey rather than from the method itself; a thorough Failure Modes and Effects Analysis (FMEA) would appear as resource-intensive for the same reason, *viz.* the need to cover all reasonable risks. If the need for completeness can be relaxed, then the analytical workload can be reduced by prioritizing the examination of loops, in the preferred order *fast+strong*, *slow+strong*, *fast+weak* and lastly *slow+weak*.

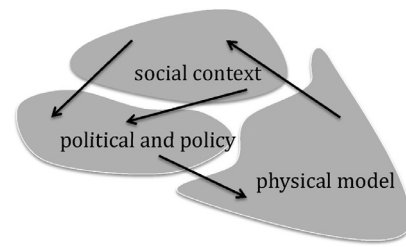


Fig. 3. Interconnection of sub-models.

For subsequent action planning for risk mitigation/control and consequences management, the process is similar to that for strategic analysis, namely that each arrow is inspected to determine what actions should be applied, subject to resource limitations, in order to condition the mechanisms underlying each arrow so as to achieve the desired system output, recognizing that there may be more than one 'system owner' judging the merit of an effect.

It is worthy of note that even the simple example shown in Fig. 2 shows the way in which the qualitative modeling links together three different but connected domains relevant to the flooding of the substation, namely the physical realities of electricity supply and flood defense, the perceptions of the victims/participants and the political realities of resource availability (see Fig. 3). It is this ability to combine the numerical and well-defined together with the ephemeral and socially constructed that makes this hybrid approach a powerful contextualization tool for detailed simulation.

Fig. 3 illustrates the general architecture appropriate for modeling risk and safety in a CHAS. The physical model (center) will be dominated by numerical modeling having an assumption of an engineering or physical reality, while the other two sub-models can either assume a single, pre-negotiated reality agreed by stakeholders or can contain multiple valuations and indeed beliefs about the validity or benefits of outcomes and, not infrequently, about the very system itself.

5. General modeling and analysis procedure

We now summarize the recommended modeling and analysis procedure, concentrating on the risk identification section of the ISO 31,000 recommendations (ISO/DIS, 2009).

5.1. Modeling

Using the architecture of Fig. 3 as a guideline, establish an influence diagram detailing the physical realities of the system-in-focus together with the associated social and political contexts.

The social context and political/policy sub-models are usually best undertaken by focus groups and care must be taken to ensure that the informants in the respective areas are sufficiently competent through experience and knowledge to represent the relevant areas. For example, it would be inappropriate for a local farmer to construct a hydrological model detailing scouring, the dynamics of water levels and other issues of physical fact. Equally it would be inappropriate for a hydrologist to construct the component of the model which dealt with the effects of flooding on morale, risk aversion by farmers and other socially constructed elements residing in the other parts of the model. This is not to say that each is forbidden from contributing to other sections of the hybrid model, merely that the modeler should take care that authority is placed where it belongs.

In the case of the model presented here, an ID was built up over a period of 10 weeks, in short workshops, the contributors to

which included specialist hydrologists, a chartered electrical engineer, together with citizens and disaster/crisis management practitioners. The process of generation was the standard one adopted in qualitative SD, where a facilitator enables the production, doing the physical diagram construction, and who then reads back the work to participants having checked offline for grammar, definition compliance and completeness with respect to the conversation from which the diagram emerged. The ID, then, although quite simple, is an accurate and agreed representation of a conversation amongst informed specialists.

5.2. Characterization of the descriptive variables

The descriptive variables in the ID are examined for *inherency* and *output significance*. These are, respectively, the extent to which a variable's value is subject to changes induced by factors outside the system (for example, *rainfall*) and the significance of the variable as a measure of output, i.e. the target of the system management. The importance of high inherency variables is that they have the potential to be instigators of exogenously derived change in the system and hence to be the causal factors for changes in the risks therein.

5.3. Loop and chain extraction and categorization

Using the well-documented methods of QSD (Powell & Coyle, 2005) extract those closed cycles of causality (dominant loops) which are significant in the operation of the system-in-focus. This is best done by a combination of automatic and inspection methods. These loops can conveniently be categorized by their speed of operation and strength of influence on the overall system outputs as judged by the stakeholders.

Chains of causality linking high inherency variables to loops containing variables of high output significance are identified at this stage.

5.4. Loop analysis and threat identification

Each (significant) loop is then examined, arrow-by-arrow to determine what factors and agents, both purposive (i.e. intentional) and unintentional may operate so as to disrupt the operation of that component of each loop. This provides an exhaustive analysis not only of threats and internal risk factors but of the likely impact of the threat or factor on the operating mechanisms of the system, what we will refer to from now on as the threat intervention mechanisms. Moreover, since the architecture of Fig. 3 requires modeling of the context in which the system-in-focus sits, the threat identification process is thorough and complete, to the extent that the model is a sufficiently broad representation of the system and context.

An important part of this threat identification process is consideration of the effects of changes in the high inherency variables upon the dynamic state of the system, and in particular, upon the behavior of the loops

This process can be time-consuming and should be carried out to a depth sufficient to ensure threat analysis of all significant dynamic loops is completed. As with any risk analysis, judgment must be applied as to the resource appropriate for the task. In general terms it is necessary to analyze fully all those loops which are judged by the informants to be significant to the system outputs.

5.5. Further analysis

There are a number of further analyzes which can be done, the details of which we leave to later work. These are aimed at the

mitigation and consequence/effect management parts of the process. As far as risk and threat identification are concerned, a useful further activity is to gather together the threat intervention mechanisms for each threat or factor. This then provides a convenient focus for the assessment and management of the threats and risk factors for the system.

6. Illustrative example – flood threat to an electricity sub-station

6.1. Physical sub-model

Fig. 5 below shows the physical sub-model, extracted from the full ID of Fig. 4. It assumes a single substation with a coffer arrangement, (i.e. a permanent concrete barrier wall to protect against high water levels in the immediate surrounding area) some run-away drainage facility and some limited emergency pumping arrangements which can be brought into play as the likelihood of coffer breach rises. The substation supplies the national grid through a regional distribution net. Ultimately electricity supply, both domestic and commercial, is made through the grid, but loss of supply from the substation will affect local consumers, a loss of supply which, in normal circumstances, can quickly be made up by regional and national provision. However, if the surrounding supply network is also under threat of loss of supply, this make-up may not be available.

To the left side of Fig. 5 can be seen some weather-derived variables such as *wind speed* and *rainfall* which, by their own direct effect and through their effect on the water-table, will prejudice the integrity of the substation and, indeed, the surrounding supply network.

Fig. 5 was constructed by the focus groups not to answer the detailed design question for the layout of the substation, but to investigate the management of substation supply failure. As such it is concerned not just with actualities – *windspeed*, *rainfall* – but in some cases with predictions and forecasts – *predicted rainfall for next 48 hours*, *potential damage to surrounding distribution grid*, *predicted wind speed* – since these latter will affect the surrounding social valuation sub-model as much as do actual system variables. The 'physical model' here, then, includes the surrounding causal factors such as weather, then physicalities of the substation itself and certain predicted variables which will affect the social valuation system, to which we now turn.

6.2. Social valuation sub-model

Fig. 6 (again extracted from the full ID of Fig. 4) shows both the social valuation sub-model (variables in **bold**) and the political sub-model (variables underlined).

The mechanisms represented here by the informants focus on perceived risk and perceived likelihood of disruption as well as on actual effects, since consumers/victims of disaster are (in the general case) are unable to measure actual risk but are predictive in their cognition. Their primary engagement here is between anticipated effect and the availability of funding long term ('projects') and short term ('maintenance'), an interaction between physical actuality/prediction, the social valuation of that prediction and the political system through the exertion of pressure for resources to be applied. This observation that political pressure and effect is achieved by socially-derived pressure resulting from both perception/prediction and by actuality is expected, but the ability to investigate the effects of these mechanisms in a disciplined and complete fashion is worthy of note.

Fig. 7 shows the links (shaded) back into the physical model as the effect of political pressure results in the (re)allocation of resources.

Social valuation

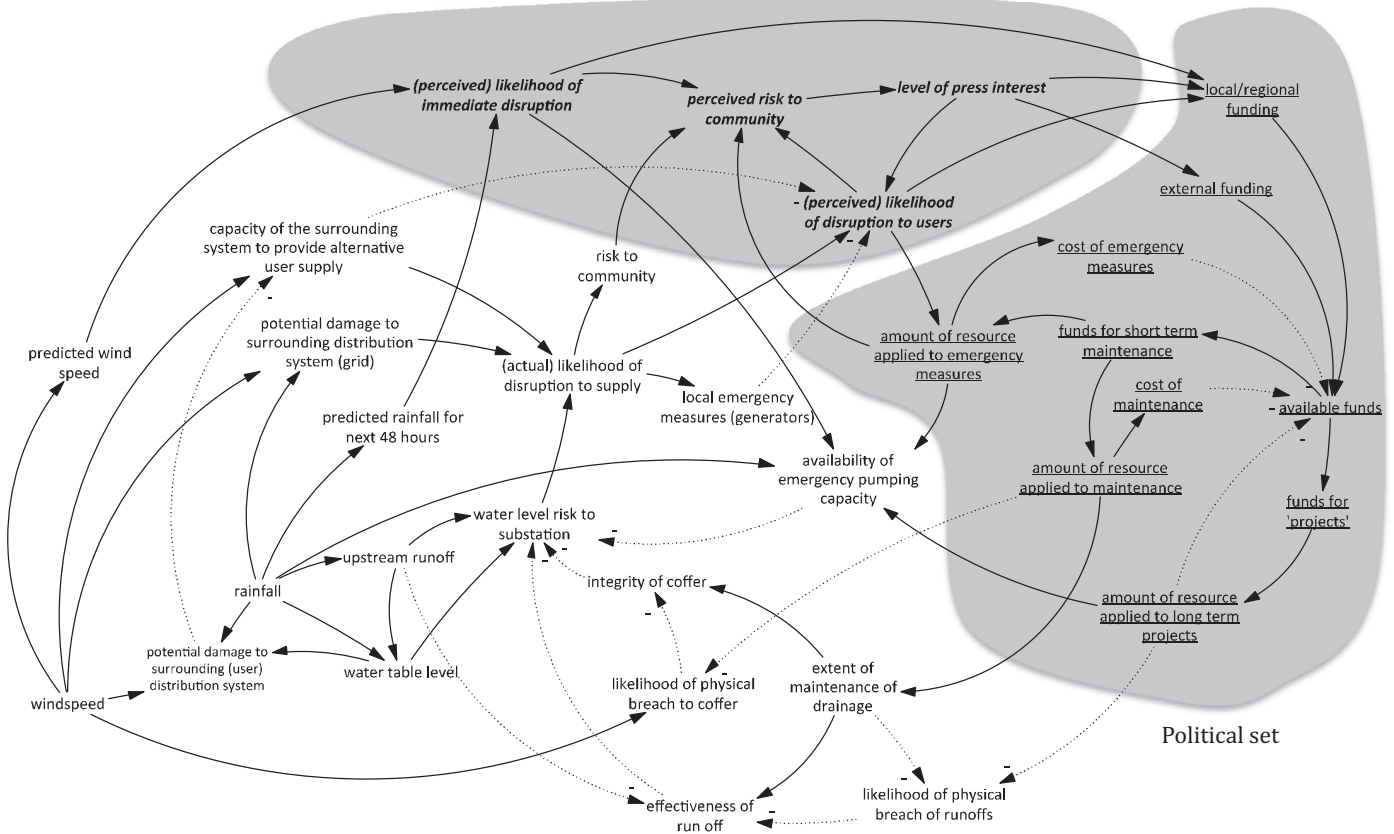


Fig. 4. Shows the full ID of the illustrative example of flood threat to an electricity substation with the three sub-models delineated.

6.3. Loop analysis

In its standard form, qualitative SD stresses the importance of identifying closed loops within the ID, the examination of which forms the basis for the identification of managerial action (Coyle, 1996, Powell & Coyle, 2005, Sterman, 2000). There are two canonical forms. The resonant (or runaway) loop, where amplification around the loop is greater than 1 and the goal-seeking form, where amplification round the loop is less than 1. In the former a change to one of the loop variables propagates around the loop, providing, in theory at least, an ever-increasing (or decreasing) effect. The argument in conventional system dynamics analysis is that if a closed resonant mechanism can be identified, it provides a potential for continuing effect from an intervention, as distinct from the ‘single shot’ of an intervention applied to an open causal chain. In the latter, the goal-seeking loop, because the amplification round the loop is less than unity, any step change decays over time.

In risk identification, however, there are issues with such a purist approach. While the continuing effect of an intervention into a closed loop remains significant, we are equally concerned with the one-off effect of a single step-change, such as (in the case of our electricity substation example here) a sudden increase in rainfall or, indeed, a decrease in funding availability for the provision of emergency resource. In both cases we need to consider whether the effect of the step change will itself be transient or whether it will, through resonant mechanisms in the system structure (i.e. loops) continue to propagate after the one-off causal event.

6.4. Inherency

Take, for example, the disruption of a ‘pulse’ of rainfall. In some system structures such a discrete event will produce an increase

in the likelihood of disruption of supply only for the duration of the ‘pulse’ of rainfall and a short time afterwards. In other system structures (say, where the effect of the rainfall increase is to cause a breakdown of the substation coffering because of increased water pressure) the effect will be catastrophic, causing a sustained and dramatic increase in the likelihood of supply loss. The approach described here allows categorization of threats on that structural basis.

Table 2 contains information on the ‘inherency’ of variables. Inherency measures the propensity of the variable to change due to factors outside the system as distinct from its propensity to change because of system effects; it is thus an indication of the propensity of the variable to act as a disruptor to the system. Thus a boundary variable with no (system) inputs will have a high inherency, whereas a highly connected variable may be subject to change but if the majority of that change derives from variables which are inputs to it, its inherency will be low. In Table 2 the variables which are shaded are considered to have the propensity to change for reasons other than changes in the variable to which they are connected. Note that this is not the same as the propensity of a variable to change in an absolute sense. For example, rainfall has high inherency because it is subject to change but not through its interaction with the remainder of the system in focus. Predicted rainfall, on the other hand is just as subject to change, but has low inherency because that change is wholly attributable to factors already represented in the system. Thirdly, press interest has a degree of inherency because although most of the press interest will be generated by the factors represented in the system, there is a possibility that there could be a rise in media interest because of events outside the narrow confines of the model of Fig. 4, say if a major flood event occurs in an adjacent area, raising afresh concerns which up, until that time, were latent.

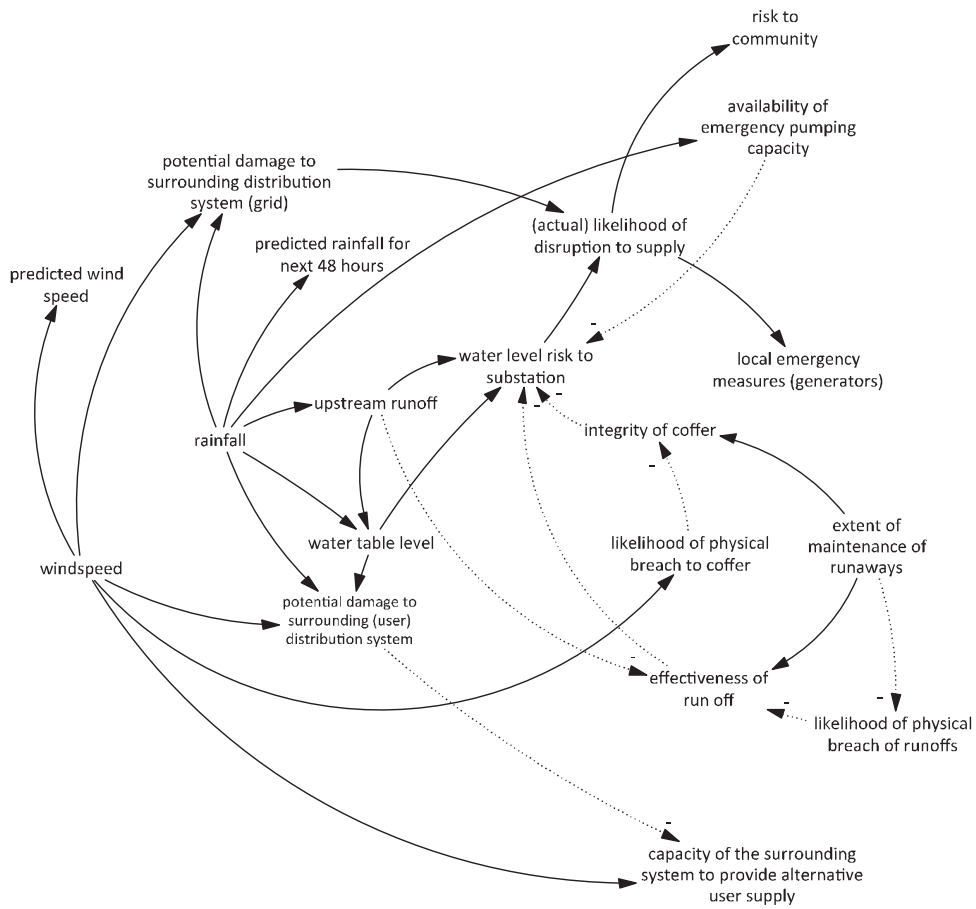


Fig. 5. Physical sub-model.

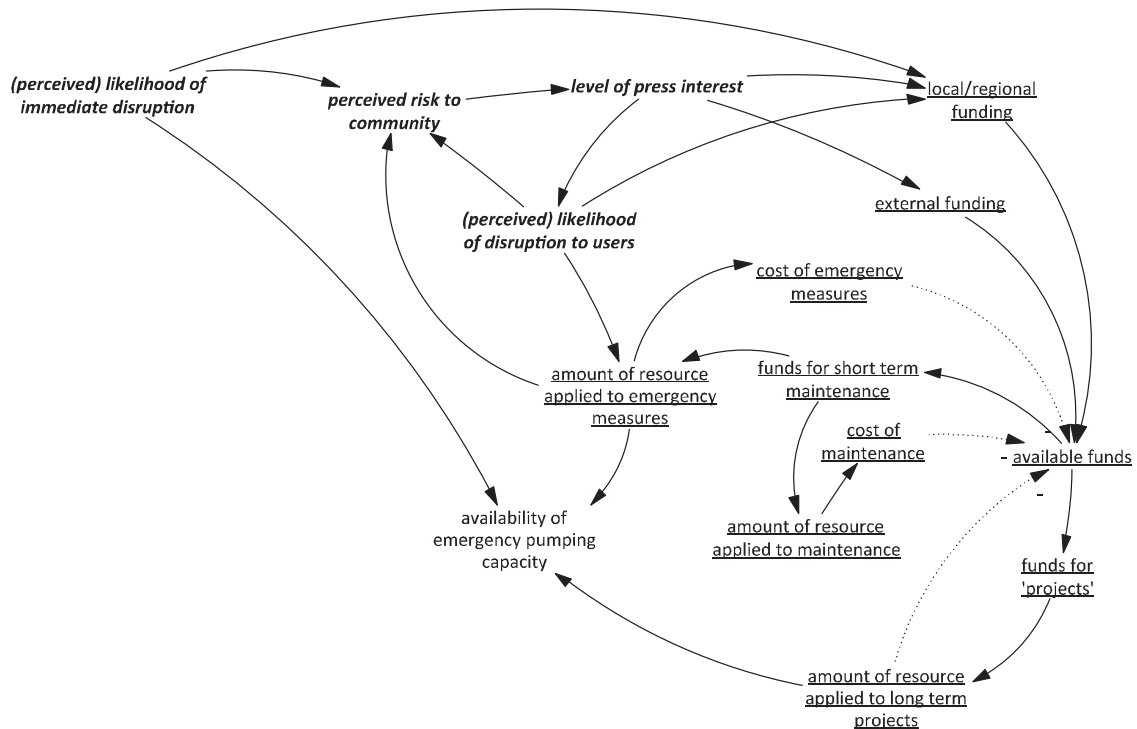


Fig. 6. Social valuation and political sub-models.

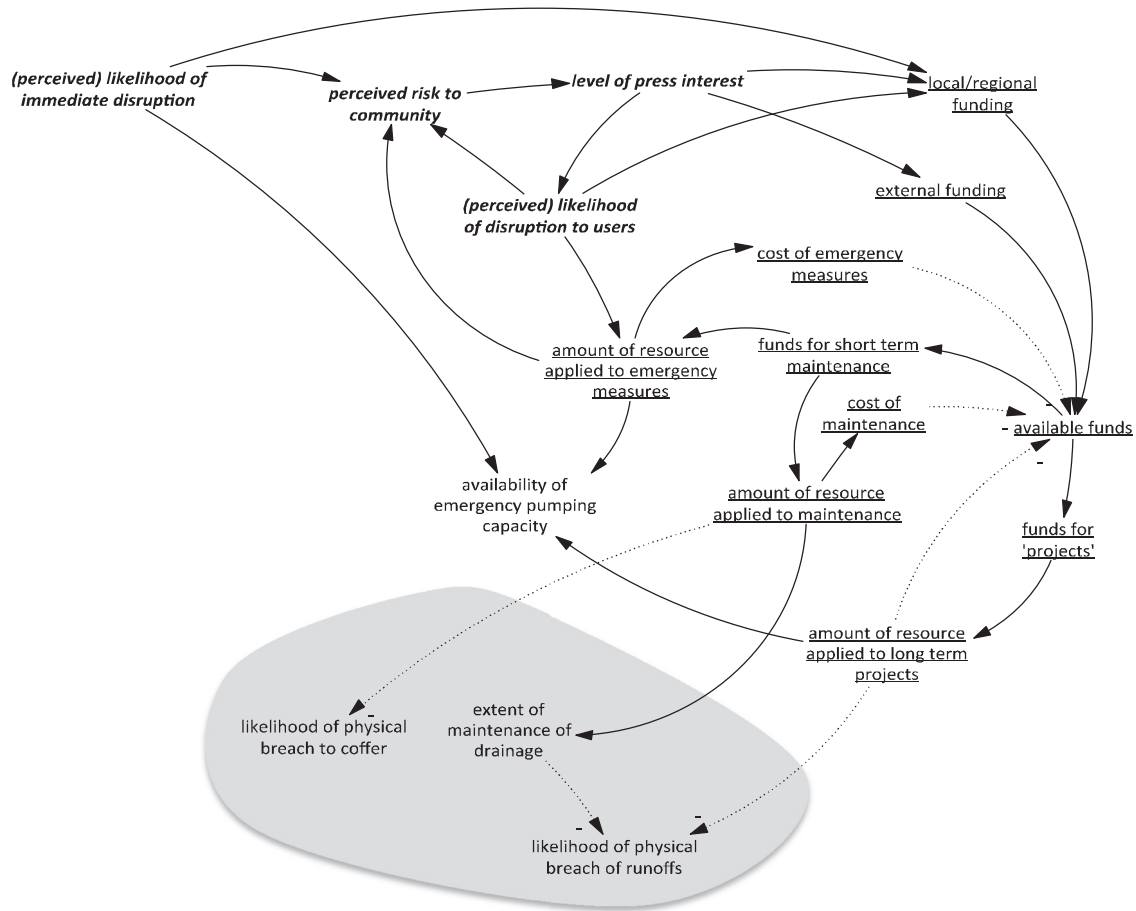


Fig. 7. Links back into physical sub-model as a result of political action.

Table 2

Tabulation of inherent mutability of variables [or ‘inherency’] and output significance (H = High; L = Low, M = Medium).

Variable	Inherency	Output
Wind speed	H	Independent variable
Predicted wind speed	L	Highly dependent on actual wind speed
Potential damage to surrounding user distribution system	L	Factors included
Water table level	L	Dependent on rainfall
Rainfall	H	Independent variable
Upstream catchment	L	Fixed capacity
Predicted rainfall for next 48 hours	L	Some possibility of exogenous risk
Water level risk to substation	–	Dependent on system variables
Risk to community	–	Dependent on system variables
Capacity of surrounding system to provide alternative supply	M	Some possibility of risks in surrounding system
Likelihood of physical breach to coffer	L	Dependent on rainfall
Availability of emergency pumping capacity	L	Dedicated to local use
Extent of maintenance of drainage	L	Factors included in model
Effectiveness of run off	L	Factors included in model
Likelihood of physical breach to runoffs	L	Factors included in model
(Actual) likelihood of disruption to supply	L	Some possibility of risks in surrounding system
Perceived likelihood of immediate disruption to supply	L	Factors included in model
Perceived risk to community	L	‘word of mouth’ dominated by local press
Perceived likelihood of disruption to users	L	‘word of mouth’ dominated by local press
Level of press interest	M	Possibility of other news stories provoking interest
External funding	L	Factors included
Cost of emergency measures	–	Dependent on system variables
Amount of resource applied to emergency measures	L	Hypothecated funding
Funds of short term maintenance	L	Factors included in model
Cost of maintenance	L	Factors included in model
Amount of resource applied to long term projects	L	Factors included in model
Funds for ‘projects’	L	Factors included
Available funds	M	Factors included in model
External funding	L	Factors included in model
Local/regional funding	L	Factors included in model

In terms of risk identification, then, we look to the variables with high inherency as being the ones most likely to be the source of disruptive changes to the system of concern to us.

6.5. Output significance

Table 2 characterizes the variables according to their output significance (right hand column), by which we mean the importance of changes to that variable as viewed from the perspective of the system owner.

There are ontological difficulties here, to be sure; it is not always clear who the system owner is or even whether there is a single incumbent. Moreover, the system owner (in the sense of the agency which directly controls the relevant resources) may not be the same as the most significant stakeholder (in the sense of the agency most affected by system outputs). We deal with these matters methodologically in a separate paper. Here it suffices to assume that the system owner is the regional distribution authority (RDA) and whose motivations are consistent with ensuring reliable, predictable electricity supply to the local community. There are nuances here; we are not assuming that the RDA will act locally in opposition to the wider interests of maintenance of supply. Neither are we assuming that maintenance of local supply will be done in opposition to the longer term interests of the RDA, so that sympathy with the surrounding political and social valuation contexts is appropriate for the RDA in determining its actions.

The right hand column of Table 2 details the importance of each variable to the system owner. It is important to distinguish here between implied importance and output importance. Each connected variable will have implied significance, but only a few will have direct impact on the stakeholders' valuation. Here we identify 6 variables of high significance, including *risk to community*, (*actual*) *likelihood of disruption to supply* and *level of press interest*. This last, together with two variables (*potential damage to surrounding user distribution system* and *cost of emergency measures*) evaluated as of medium significance, reflect the wider interests of the RDA in mediating between the narrow responsibility to provide supply to users and the need to maintain strategic relationships.

6.6. Chain/loop identification

The heart of the risk identification analysis method using dynamic system knowledge is in understanding and examining the connections between variables of high inherency, likely to cause disruptions to the system state (instigating variables), and variables of high output significance. The former capture the inputs to the system from which risks derive; the latter are the basis for the evaluation by interested parties of the system output or state.

We can therefore consider the topology of the system under examination as consisting of two related parts, namely that portion comprising the set of variables which form elements of loops (connected variables) and a set of instigating variables which have high inherency and which are capable of creating disruptions to those loops. It should be observed that this latter set can include both variables which are not members of loops and connected variables.

The process of analysis then, is to identify key dynamic loops and to examine these for the effects of high inherency variables in order to determine the effect of disruptions produced by changes in the instigating variables. This then provides an auditable basis for the identification of risks material to the system output.

The standard approach in qualitative SD is to use a combination of tool-based methods and visual inspection to identify dominant loops. The application used here, Vensim ©, allows the tabulation of loops which contain a particular highlighted variable as well as the tabulation of causal connections into and out of a selected variable.

Consider Fig. 8. Here we have separated into the delineated area all those variables which form components of at least one loop. This separation is straightforward; the variable *rainfall*, for example has no causal arrows entering it. Hence, it cannot be part of a closed loop, and by extension, neither can *upstream inflow* (the quantity of water upstream of the substation which has the potential to overwhelm its coffer) since the only input to the latter is *rainfall*.

Fig. 8 also distinguishes instigating variables (in boxes) and high output significance variables (in hexagons). The essence of our procedure is, through a tabulated approach, to identify the effects of the boxed variables, via the system dynamics, on the output variables.

The instigating variables can affect the loop dynamics indirectly. See Fig. 9, where the connections between rainfall, an unconnected instigating variable and connected variables are elucidated. Rainfall can affect amount of resource applied to emergency measure directly, but also affects, for example, *perceived risk to community* through the intermediation of *predicted rainfall* and (*perceived*) *likelihood of immediate disruption*.

Were we to follow a narrow loop-based analysis, we would fail, then, to identify risks deriving from the instigating variables, seen as extra-systemic critical event source variables, by which we mean those variables such as *rainfall* and *windspeed* which fall outside the system in that neither the system owner nor the variables defining the system have any influence over them.

6.7. Procedure

The procedure adopted, then is, to identify

- The loops present in the ID and characterizing them as resonant or goal-seeking, slow or fast and strong or weak. See Table 3, which contains a selection of loops drawn from Fig. 4 and selected on the basis of their perceived effect on the system performance output.
- For each loop identify the initiating variables which can materially affect, either directly or indirectly, the loop performance.
- For each loop, tabulate the risks deriving from the effect of the relevant instigating variables.

7. Results

Using the aforementioned procedure results in a set of structures which have been extracted from the ID and which constitute the most influential causal paths by which instigating variables can affect the significant output of the system.

Even this relatively simple ID contains over 100 loops, the complete analysis of which would be both onerous and unnecessary, not least because of the duplication and overlapping of many of the loops. Selection of the appropriate subset is carried by visual inspection, ensuring that loops which contain the high output variables are taken into consideration and that, at least for the risk identification problem, all accessible parts of the ID are covered by the set of loops selected for analysis. Five loops are shown (column 2) and described briefly (column 3) in Table 3, the full set consisting of some 20 considered to provide adequate coverage.

Column 4 of Table 3 then indicates whether each loop is *fast* or *slow*, *strong* in its system effect or *weak* and *resonant* or *goal-seeking*. This typology allows prioritization of loop analysis, since, for example, *fast*, *strong resonant* loops will have the most effect on system performance when disrupted by changes in instigating variables, while *weak*, *goal-seeking* loops will be less influential.

The next step is to identify the manner in which the instigating variables are likely to have an effect on each loop and this is summarized in column 5 of the table.

Consideration of the effect of changes in the dynamic state of the loop, particularly with regard to the effect on the loop performance of a step change in an instigating variable, allows the content of column 6 to be built up, and this constitutes the risk analysis which is the aim of the process. Mitigation and control measures associated with these risks can then be carried out in an appropriate manner, again informed by the visibility of the underlying system dynamics.

8. Discussion and conclusion

Examination of the identified risks (column 6) shows that many of them thrown up by the process are to be expected; it is obvious, for example, that a step change in rainfall would produce the risk that (03–6) “Drainage capacity [would be] insufficient in capacity for predicted rainfall increase” or that (04–2) “**available funds** may be subject to external reduction/increase”. Others are less intuitive, such as the risk (05–2) that “arrival of emergency equipment [could be] misinterpreted as indicating inevitable disruption OR as evidence that there is no residual risk to community”, supplemented by (01–4) “Increased deployment of pumps and other equipment causes public alarm over severity of the situation”.

The appearance of such risks illustrates the ability of the approach to encompass risks which fall across the boundaries of the three sub-models, allowing, for example, communication between parties focusing on physical aspects of design and parties fusing on operational matters to take a common connected view. In the case of the unexpected risk that the arrival of pumping equipment, intended to allay public concern and reduce the actual likelihood of supply loss, could cause a rise in public concern with undesirable effects elsewhere, is a good example of this cross-communication.

It is easy retrospectively to claim that such a risk would be “obvious to an experienced manager/designer” but the adumbration of these cross-functional risks can only help to improve the risk identification process as a whole.

8.1. Scalability considerations

The example presented here is, for the purposes of illustration, a compact and limited one, but the scalability of the method to larger systems is entirely possible. One of the characteristics of soft OR methods (including the System Dynamics corpus utilized here) is their ability to adjust the resolution of modeling according to the needs of analysis. Thus, in the present example, the disaster manager’s need may well be to identify detailed risks, since the extent of the problem is limited. In the case of a CHAS of much wider extent (for example, in the case of flooding of a whole region) the risk identification, at least at the initial assessment period, can be more generalized, working down in resolution as policy itself more becomes more focused in its application.

The method has been applied to large scale flooding examples (the UK Somerset Levels and Thames Valley floods of 2014) and, indeed to the highly complex management of the Ebola epidemic in West Africa of 2014–2015), the reports of which are in preparation, and which form extensions of the present work towards the issues of human agency and knowledge gaps, respectively.

8.2. Critique and further work

There are a number of counter-arguments which could be leveled at this approach to risk identification.

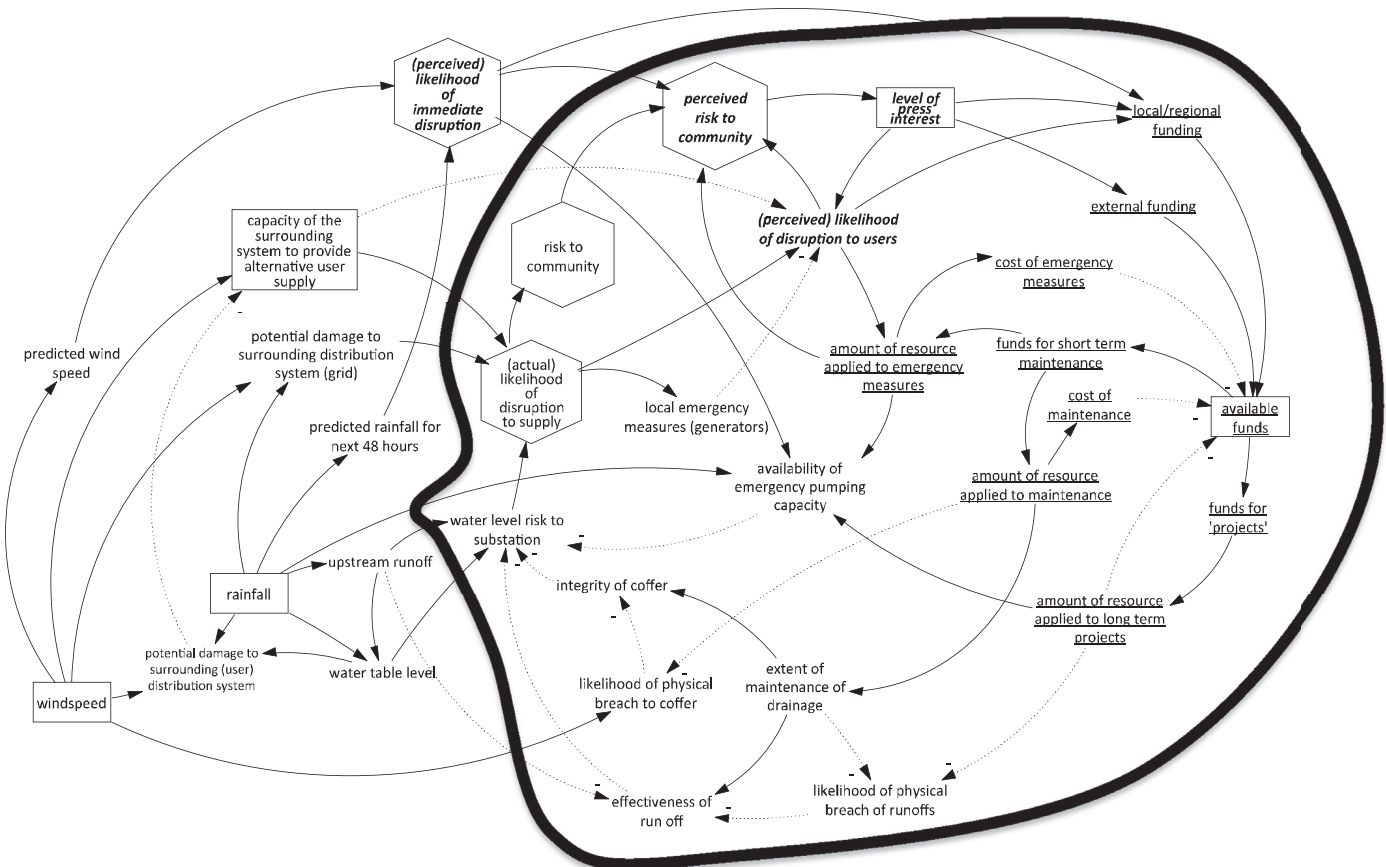


Fig. 8. Delineated area includes all variables capable of being in loops. Initiating variables in boxes, output variables in hexagons (as Table 3).

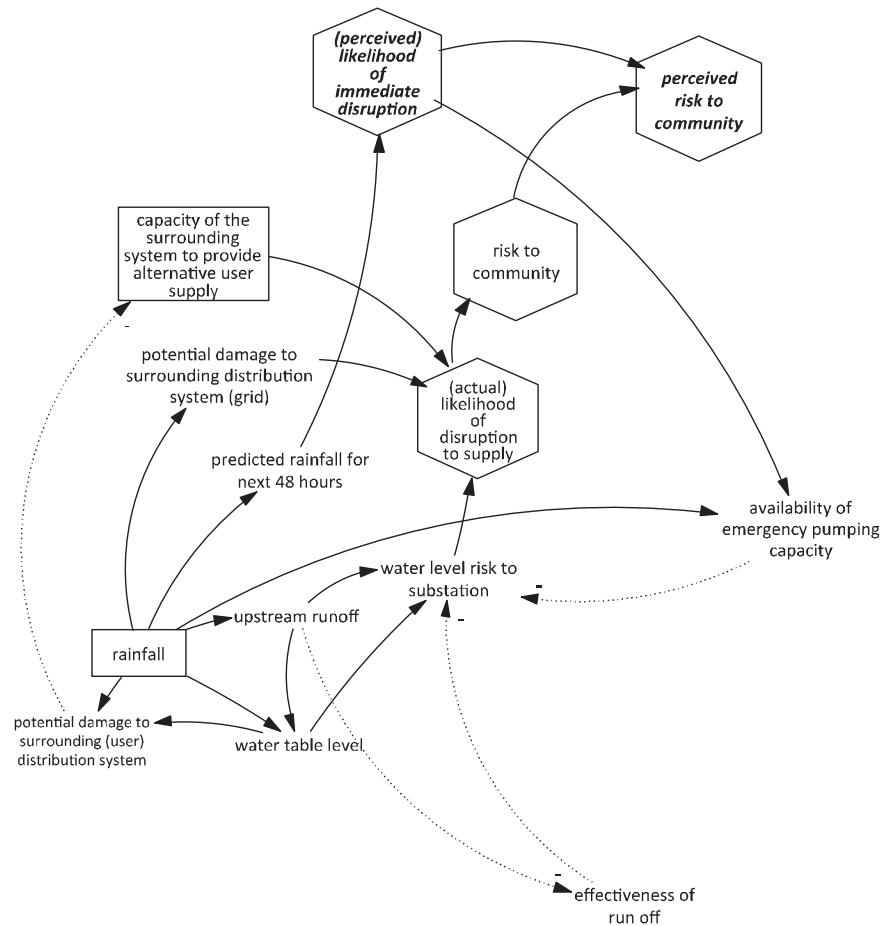


Fig. 9. Chains connecting rainfall with high significant output variables.

Firstly, the approach appears deliberately to reject the use of numerical data. In fact the qualitative SD approach allows the mobilization of numerical data where it is available, but is not limited in its analysis by the absence of such. In addition to the obvious argument that not all factors, particularly those in the social valuation and logical sub-models, can be made numerical, the concentration on structural analysis allows generalizable observations to be made about system behaviors. Now admittedly those generalized statements are less precise than those deriving from a numerical model, but they do, in contrast, allow a breadth of analysis which the narrow strictures of quantitative work necessarily forbid.

Secondly, we are aware that the method elucidated here is time consuming, if all potential system dynamic loops are to be examined. In many cases rich IDs can exhibit many thousands of loops. This, however, is a problem faced by all dynamic analyzes and, moreover is one shared with all thorough risk analysis approaches. One would observe, first, that the practice of selecting loops for examination on a visual inspection basis is common and well-documented and, second, that a thorough risk analysis is resource intensive not because of the complexity of the modeling so much as because of the need for thoroughness in the risk identification task. Completeness of analysis militates for effort in that analysis.

Further work in this area continues to establish sound means of incorporating multiple viewpoints into the valuation analysis and in establishing the role of knowledge in the instigation of risks in systems and further papers will cover these aspects.

Of particular importance is the identification of how the ability of the qualitative method used here can be used to target subsequent investigations of a more numerical nature. While it is true that much of the system knowledge deployed in this approach to risk identification is by its nature qualitative, examination of the loops contained in Table 2 will show that there is implicitly much which can be expressed in a quantitative fashion. Indeed System Dynamics as a body of knowledge (Sterman, 2000) is well suited to this numerical simulation of quasi-numerical system variables. It possesses the capacity to progress from an ID to a simulation structure relatively easily and the environment deployed here, Vensim © has an automatic simulation structuring tool within its standard embodiment which supports direct numerical simulation extension from the qualitative approach deployed here.

On a more localized basis, the identification of those variables which are both significant in the system dynamics and are subjective to numerical expression proceeds easily from such tabulations as Table 2. The method of numerical definition of those variables will, of course, vary from variable type to variable type. Rainfall is easy to measure empirically, whereas level of press interest, may not be so convincingly expressed. Some variables, such as level of public concern, may have to be explicitly investigated by questionnaire, entraining all the limitations of structured surveys. In all cases, however, the relevance of further numerically-based investigations can be targeted more effectively by the auditable approach presented here.

Table 3
Summarizes the analysis for the substation example of Fig. 4, covering a selection of loops for the purposes of illustration.

No.	Loop diagram	Description/Objective	Type	Disruptions (chain effects)	Inherent risk(s)	
01		Public perception drives press interest resulting in the application of emergency resources but this, itself increases perception of risk	Strong Fast Resonant	Rainfall Windspeed Available funds	<ul style="list-style-type: none"> • Perceived risk to community • Amount of resource applied to emergency measures • Perceived risk to community • Amount of resource applied to emergency measures 	01–1 A rise in public perception that emergency services or other essential infrastructure is at risk may cause unwelcome press interest. 01–2 Press focus may cause concern in the public mind over the possibility (real or imaginary) of supply disruptions 01–3 Public pressure may militate for deployment of emergency equipment, depleting flexibility 01–4 Increased deployment of pumps and other equipment causes public alarm over severity of the situation.
02		Increased press interest will drive public perceptions that supply is threatened and therefore perceived expectation of risk.	Strong Fast Resonant	Rainfall Windspeed Available funds	<ul style="list-style-type: none"> • Perceived risk to community • Perceived risk to community • Perceived risk to community (through emergency resource application) 	02–1 As 01–1 02–2 As 01–2 02–3 Public concern over potential supply loss fuels wider concern over risk to infra-structure and emergency services
03		Concerns about disruption motivates local/regional administrative authorities to allocate funds aimed at maintaining drainage so that flood water pulses can be run off. This reduces the risk of defenses being overwhelmed which reduces risk.	Strong Slow Goal-seeking	Rainfall Windspeed	<ul style="list-style-type: none"> • Water level risk to substation • Amount of resource applied to emergency measures • Water level risk to substation 	03–1 Public concern is artificially heightened resulting in inappropriate pressure to increase funding, jeopardizing good long term financial control 03–2 Public pressure demands inappropriate short term resource allocation (see 03–5) 03–3 Time pressure and need for visible action on physical state of runaways induces sub-optimal project performance. 03–4 Poor physical state of drainage increases likelihood of defenses being overwhelmed. 03–5 Need for allocation of resources to cosmetics of infrastructure diverts effort from remedial work. 03–6 Drainage insufficient in capacity for predicted rainfall increase
04a,b		Two loops a and b summarize the financial reality that short and long-term expenditure reduces the available funds.	Strong Fast Goal-seeking	Available funds Rainfall Level of press interest	<ul style="list-style-type: none"> • Direct effect • Amount of resource applied to emergency measures • Available funds 	04–1 Threat that over-expenditure on short term measures will exacerbate pressure on longer term projects and vice versa. 04–2 Available funds may be subject to external reduction/increase 04–3 Effect of weather will induce unavoidable expenditure on short-term measures, thereby unexpectedly reducing available funds 04–4 Sufficient press interest may distort funding processes

(continued on next page)

Table 3 (continued)

No.	Loop diagram	Description/Objective	Type	Disruptions (chain effects)	Inherent risk(s)		
05		<p>An increased likelihood of disruption instigates the deployment of local supply measures (generators). As a result local concern falls, taking pressure off the need to apply emergency resources in to pumping, so that, counter-intuitively, the disruption likelihood rises further.</p>	Fast	Rainfall	<ul style="list-style-type: none"> • Water level risk to substation • Actual likelihood of disruption (through damage to surrounding grid) • Perceived likelihood of disruption • Amount of resource applied to emergency measures 	05–1	Risk of over-stressing responsive supply-maintenance measures at the expense of preventative measures
			Weak	Windspeed	<ul style="list-style-type: none"> • Actual likelihood of disruption (through damage to surrounding grid) • Perceived likelihood of disruption • Amount of resource applied to emergency measures 	05–2	Risk of arrival of emergency equipment being misinterpreted as indicating inevitable disruption OR as evidence that there is no residual risk to community.
			Resonant	Available funding	<ul style="list-style-type: none"> • Amount of resource applied to emergency measures 	05–3	significant rainfall and/or wind may cause disruption to surrounding supply grid causing rise in likelihood of disruption
				Press interest	<ul style="list-style-type: none"> • Perceived likelihood of disruption 	05–4	High levels of press interest may exacerbate public concern causing over-reaction
						05–5	as 04–2

Acknowledgments

The project was supported via the University of Exeter's Bridging the Gaps project [funded by the EPSRC's Bridging the Gaps initiative (grant reference EP/I001433/1)]. Material deployed in the work can be accessed by direct communication with the corresponding author.

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