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Human Agency in Disaster Planning: A Systems Approach

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Current approaches to risk management place insufficient emphasis on the system knowledge available to the assessor, particularly in respect of the dynamic behavior of the system under threat, the role of human agents (HAs), and the knowledge available to those agents. In this article, we address the second of these issues. We are concerned with a class of systems containing HAs playing a variety of roles as significant system elements—as decisionmakers, cognitive agents, or implementers—that is, human activity systems. Within this family of HAS, we focus on safety and mission-critical systems, referring to this subclass as *critical human activity systems* (CHASs). Identification of the role and contribution of these human elements to a system is a nontrivial problem whether in an engineering context, or, as is the case here, in a wider social and public context. Frequently, they are treated as standing apart from the system in design or policy terms. Regardless of the process of policy definition followed, analysis of the risk and threats to such a CHAS requires a holistic approach, since the effect of undesirable, uninformed, or erroneous actions on the part of the human elements is both potentially significant to the system output and inextricably bound together with the nonhuman elements of the system. We present a procedure for identifying the potential threats and risks emerging from the roles and activity of those HAs, using the 2014 flooding in southwestern England and the Thames Valley as a contemporary example.

KEY WORDS: Human factors; soft systems; systems modeling

1. INTRODUCTION

This is the second of a series of articles(1–3) concerned with the identification and assessment of system risk as part of the process of identifying appropriate policies for the control and mitigation of risks under inevitably limited resource availability.(4) The focus is on safety and mission-critical systems, particularly those that contain human agents (HAs) whose decisions and actions form an inextricable part of the system assets, but noncritical systems also benefit potentially from our approach. We refer to this class of systems as *critical human activity systems* (CHASs). Examples are air traffic and shipping control, railway network management, health-care systems, and infrastructure systems (infrasystems), such as electrical distribution and flood control.(5) We distinguish between the physical infrasystem, the interactions of the HAs participating in that infrasystem, and the policy subsystem around it.

We have observed elsewhere(1) that there are four shortcomings in existing approaches to the systematic identification of risk,(6–18) namely:

(1) A reluctance to mobilize what is known about the dynamics of the system in focus and, in particular, the causal mechanisms experienced by and understood by the managers and inhabitants of that system.

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(2) A lack of a structured approach to the analysis of the risk presented and managed by the HAs in a CHAS.
(3) A paucity of attention in risk analysis to the knowledge (as distinct from information) deployed by those HAs.
(4) An inability effectively to take into consideration the multiplicity of viewpoints, system definitions, and valuations of various stakeholders.

In this article, we concentrate on the second of these points, deploying a technique well known in more general strategic analysis and emerging from the system dynamics community, to assist in the identification of risk mechanisms in a way that explicitly includes the involvement and actions of individuals and groups inhabiting and associated with the system in focus.

To illustrate the method, we model the flood events of the 2013/2014 Somerset Levels in southwest England, using a modeling architecture that covers the physical infrasystem, the social valuation context, and the policy surround.(1)

1.1. Definitions, General Approach, and Scope of Article

1.1.1. *Role of HAs in CHASs*

CHASs, by definition, are systems subject to management where the HAs are entwined with a physical substrate, known as the *infrasystem*. Their interactions with this infrasystem are manifold. They can be passive recipients of system behavior, observers and commentators on that behavior, or indeed components of it, since they can be programmatic or conscious decisionmakers, responding to knowledge or information inputs and taking action. Of course, as decision-making system components they are subject to irrationality, bounded rationality,(19,20) and other sources of unpredictability. Nevertheless, within the CHAS they are components whose inputs and outputs are linked with other human and infrasystem components. For example, to the extent that the citizens of a flooded area control run-off resources as flood risk increases, they open or shut sluices, barriers, and drains according to their own judgment, acting as responsive system components in a way familiar to all system designers.[4]

Lastly, they can be system owners and managers, implying a degree of autonomy over the policies enacted within the system and, by extension, the definition of the system itself.

1.1.2. *Ontology*

Before proceeding to provide further clarity of these different roles (to make sense of the extensive literature on the interaction of HAs with CHASs), it is appropriate to note an ontological difficulty deriving from the presence of humans in the system itself. The effect of this is to render the ontology of the system socially constructed (at least in part), as distinct from the conveniently positivist assumptions that can be made about the infrasystem. We have observed elsewhere(1) that there are three intersecting subsystems in CHASs—namely, the infrasystem, the social subsystem in which it is embedded, and the political subsystem that, eponymously, produces the policy on which basis the system is resourced and judged. Table I shows the different ontologies of these subsystems.

We see, then, that at least part of the system in focus is multiply defined by its participants. This requires a multiple representation and hence parallel analyses of the different system definitions, and we delay treatment of this well-known general systems problem(21) for the case of risk identification until a later paper. For the moment, we adopt the stance of a detached observer, where we attempt to capture the varying views of the participants by expanding the system representation to include different hypotheses. We will see several dilemmas of policy emerging from this treatment of the different valuations of system output and in some cases from different understandings of the infrasystem by participants.

1.1.3. *Roles of HAs in System*

The various roles of the HAs associated with a CHAS can be characterized by three distinguishing factors: (1) passivity, the extent to which they are active or passive in their role; (2) autonomy, the degree of autonomy that they possess in their interactions with the system; and (3) abstraction, being the extent to which they are acting in the domain of the intangible or the physical.

Table II shows the various combinations of these three characterizing factors, from which we can create a simple taxonomy of roles.

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[4] The system engineer's common description of humans as "wetware," in linguistic resonance with software, firmware, and hardware, has a certain irony in this example.

Table I. Ontological Assumptions of Component Subsystems

Subsystem	Description	Ontology	Implication
Infrasystem	Physical elements of the system in focus (e.g., hydrology, geography, hydraulics)	Positivist	Can be defined on a single, observed, essentially undebated basis
Social subsystem	Interactions of society in which infrasystem is embedded (e.g., press commentary, economic effects, perceptions of flood victims)	Socially constructed and plural (many valued)	Many participants will differ in their perceptions, valuations, and even definitions of the architecture and scope of the system
Political subsystem	Surrounding system through which resources are allocated and overall system behavior judged (e.g., regional and national government policy determination processes)	Socially constructed but singular	While the process of determining policy is multivalued, the output (i.e., published policy) can be treated as well defined, albeit mutable

Table II. Taxonomy of HA Roles

		Abstraction	
		Physical	Abstracted
Passivity	Passive	*Low autonomy* ***Victim*** Passive recipient of system effects without any channel of action	*Low autonomy* ***Observer*** Detached from system effects but able to observe without taking action or communication
		High autonomy ***Inhabitant*** Recipient of system effects without channel to action, but able to remove self from system	*High autonomy* ***Commentator*** Detached from system effects but able to publish commentary and contribute to others' cognition
	Active	*Low autonomy* ***Operator*** Programmatic interactor with system; not empowered to change system definition	*Low autonomy* ***Analyst*** Observer of system behavior and definition: able to create cognitive product
		High autonomy ***Participant*** Decision-making operator, able to interact with system, creating rules; able to redefine system architecture and enact rules	*High autonomy* ***Policymaker*** Able to define system outputs and create valuations; creates but does not enact rules

These roles can overlap. At the passive, low autonomy end, a HA we have characterized as *victim*, can, of course, also be an *observer*, and despite any disempowerment at the physical level may, conceivably, also be in a position to offer cognitive input to policymakers as an *analyst*—a *participant* who can also act as a *policymaker* is in the powerful position of being able to define the valuation of system outputs, to alter architecture, and to create rules and enact them. We might refer to such an agent as a *system-owner*.

In these various and diverse roles, as participants, inhabitants, valuers, and definers of the CHAS, the HAs are also originators of *risks and threats*, sometimes through purposive action and sometimes through unconscious action or inaction. By virtue of their capacity to act sentiently, they are also *risk mitigators and controllers.*

1.1.4. Risk Management Process

Risk management in general usage 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 that may or may not be reified in a particular circumstance. We shall refer to the object of this analysis as a system, since, for it to be worthy of consideration, it will be of a complexity greater than that of a single, undifferentiated event. For example, one would not perform the risk analysis of a flood event by considering it as a single, isolated, hydraulic phenomenon. It is not the flood in and of itself that is the subject of analysis, but the effect of the flood on the environment and society in which it takes place, accepting, of course, that the physical characteristics of the event are the root cause of these wider effects.

Risk management as a process, then, moves from identification and assessment to control, mitigation, and consequence management, seeking to accommodate inevitable resource limitations within an action plan aimed at satisfying a set of outputs or consequences of the causative risk event. Frequently, these action plans present dilemmas, opposing options for action, which can emerge from a number of sources. First is the inevitability in a complicated system that an intervention aimed at a particular system effect will cause, at the same time, unsought and unwanted effects. These unsought effects are an emergent property of the interconnected nature of the system itself, resulting from the inevitable interactions of competing or coexisting dynamics within the system. We distinguish between these and other unsought effects deriving from some lack of knowledge of the system. Second is a set of dilemmas resulting from disagreements about the desirability of particular system outputs. Third is a set of dilemmas emerging from different beliefs of the architecture of the system itself.

We are now in a position to make sense of the extensive literature on the role of humans in system behavior (what is often referred to as human factors) in the specific context of risk identification.

1.2. HAs and Risk

It is clear from a review of both academic and practice literature that there is a clear acceptance of the role of human agency in risk management.(22) A vocabulary in frequent use is that of “human factors” where the human is seen in various roles, such as the creator of risk and the manager or mitigator of that risk. In the role of risk creator (*operator* in Table I), there is emphasis on compliance or noncompliance with safety signals, such as (in railway terminology) signals passed at danger (SPADs). Here the HA is seen as an element of the system, but one that is essentially a switching component.(23) A more developed position looks at the role of the HA as a cognitive element (*analyst* in Table I),(24) for example, as the supervisor of a shipping control system or an aircraft. In the latter domain, the volume of work by aviation medicine institutes in many countries is very large.(25) Here the emphasis is on the ability of the HA to make sense of situations, thereby creating an internal problem (a cognitive act) that is then “solved” (more accurately “responded to”) by appeal to a preformed set of responses. There is little present in this literature in the way of rule creation (*participant* in Table I). We are critical of the tendency in this literature to generalize the context of the HAs (seen as operators or participants), rather than dealing with the specifics of the system they inhabit and, specifically, the specific interactions of the HAs with that system. This is not to say that general advice on, for example, cognitive stress arising from workload is not useful.(23) It is more that the focusing of that advice within the context of a particular system will make it more effective. Moreover, we argue that a generalized approach is inefficient because the consequences of cognitive failure (as a continuing example) are much more severe in one system environment than another.(26) For example, a fast-moving single-operator context, such as that of a single-seat combat aircraft, requires different cognitive support compared with that of a submarine control room, where cross-comparison and coproduction of the cognitive product can be made by a number of HAs over a more generous time scale.

A second, but related literature is that of human-machine cooperation.(27) Here the emphasis is on designing the interfacing of the human operator with the machine (usually limited in definition to a computer). Bearing in mind the importance of such design matters, it is not surprising that the literature and underlying work is extensive and well-funded. Again, much of the work focuses on general design principles rather than risk analysis specific to a particular system and falls short in terms of the specific analysis of the role, contribution, and effects of the HA.(28–30)

We find little in the way of study of the complex ontologies discussed briefly above; the emphasis is almost completely upon the infrastructure, thereby, in our view overfocusing on what is controllable, in design terms, rather than on the debatable/negotiable/indeterminate content of the other two ontological domains. While there is some prior work in the area of society models,(31) for example, this again tends towards the generalized rather than the specific.

System approaches to the analysis of risk are numerous, often advocating a general system approach where interventions and effects are seen to be multiply connected and where, as consequence, mitigating interventions need to be made with the understanding that unwanted and unexpected side-effects may/will result.(32–37) One or two sources have, indeed, applied this general understanding to environmental(38) and even flood risk analyses, specifically.(39) There is some existing use of system dynamics within risk analysis, both in a general sense,(40,41) for the purposes of validation(42) and as a support for the cognitive process so central to risk analysis.(43)

System approaches and system dynamics (as a particular technique), then, are well-respected approaches in the risk analysis literature, and yet our search of relevant articles adumbrates little in the way of operationalization of these concepts. Our contribution does not lie, therefore, in the introduction of system concepts to risk analysis. We do not seek, either, to claim an improvement in the product of the human factors or even the human-machine cooperation approaches in and of themselves. Rather, our article seeks to improve the effectiveness of risk analysis in two complementary areas—namely, (1) the operationalization of a system-based method of assessing risk in particular systems, by the inclusion of specific human agency, and (2) the extension of the scope of this form of risk assessment into CHASs, requiring a sensitivity to the three ontologies discussed above.

1.3. General Approach

The essential requirement, then, that emerges from the intersection of the realities of HAS operation and the approaches taken by practicing risk managers is to provide a methodology that links the effective generalities of the human factors approach and the specifics of risk assessment for a particular system.

The method we have developed, to this end, consists of the following steps:

1. *System modeling*: Usually in discussion with informants in a focus group or groups, a qualitative system dynamics (QSD) model is constructed,(44) covering the three subsystems of Table I.
2. *Attribution of HAs*: The QSD model, again in consultation with appropriate informants, is populated, arrow by arrow, with sets of actors (or agents) who, in respect of the causal connection implicit in the arrow, have an effect either on the strength of that connection, or its speed of operation.(45) These agents can be individuals, groups of individuals without formal identity, or functional groupings possessing formal identities such as "The Police" or "City Hall."
3. *Assessment of loop dynamics*: By inspection, the dominant loops are identified, being those that have the greatest predicted effect on the overall system behavior. These are characterized and prioritized for this analysis according to the speed and strength of their contribution to overall system performance.(1,44)
4. *Threat identification*: By consideration of the role, motivation, and capacity for effect of each HA in each relevant link in the key loops, the potential for each agent to affect system output is assessed. By consideration of the channel to action (i.e., the dynamic mechanism that would be affected by the HA's action) threat mechanisms are identified. Although it forms no part of the procedure elucidated here, consideration of the motivations of HAs in the context of their capacity for and channel to action provides some basis for a probability judgment of the likelihood of intervention of each HA in respect of each relevant interaction mechanism.
5. *Mitigation identification*: Appropriate limiting actions are identified to minimize the effect or likelihood of the threats identified at stage 4.
6. The identification of specific *policy dilemmas* has proved useful in practice. These potential conflicts of resource allocation or policy effects derive from a variety of sources, including diversity of system definition, diversity of effect valuation, the coexistence of competing hypotheses of behavior, and resource competition.

The key steps in this procedure are stages 4, 5, and 6, the earlier steps being well known in the QSD literature.(46) In these latter three steps, consideration of three aspects come together, namely, the system dynamics, the role and positioning of the human actors in that system, and the motivations of those actors. This concatenation of context, agent, and (plural) objectives, particularly within the specifics of a system, provides an enhanced support to the extensive general capabilities of existing approaches to human factors in risk studies.

1.3.1. Contribution and Utility of the Work

The main contribution of the technique we propose in this article, then, is in the identification of the interactions of HAs with a CHAS, particularly in respect of the risks confronting the system and its managers. Our technique puts specific emphasis on agent-based analysis. It is appropriate, therefore, to compare it with the numerical evaluation of a system using agent-based approaches and agent-based simulation (ABS) in particular. ABS has widespread application in the context of several CHASs, such as healthcare and emergency planning and evacuation, as well as agent-based social simulations. It is a simulation technique that models the overall behavior of a system through the use of autonomous system components (agents) that communicate through the exchange of messages. The behavior associated with an agent determines its role in the environment, its interaction with other agents, its response to messages from other agents, and whether its own behavior is adaptable.(47) Thus, in agent-based simulation the role and interactions of the agents are predefined and limited in extent compared with the self-defining HAs of our approach.

For the example of the flood case of this article, identification of the different categories of HAs (such as local farmers, environmental agencies, press and media) and their relationships with the system is vital prior to the development of an ABS model. The qualitative politicized influence diagram (QPID) approach allows us to do this through the systematic identification of the specific roles of the HAs within the dynamic structures of the system.(44,45) Although this is not the focus of this article, such an approach allows the effects of the HAs upon the system outputs to be systematically identified so that policy options available for the management of those risks can be illuminated. In turn, since the role of the HAs in introducing, controlling, managing, and mitigating risk can be better understood, better, more broadly understood system design and requirements capture can result.

The approach here differs from fault-tree or event-tree analysis methods, with which risk practitioners may be more familiar. Event trees or fault trees are both types of logic trees that relate a series of connected events to their consequences, and attach probabilities to estimate risk as a combination of probability and consequences.(34) The key difference between event- and fault-tree analyses is the direction of the logic. An event tree starts with an initiating event, and uses inductive logic to assess the onwards consequences. Molinari and Handmer(48) adopted an event-tree analysis to assess how humans would respond to a flood warning, accounting for whether an individual would trust or understand such a warning. A fault tree, in contrast, uses deductive logic, placing the unwanted consequence as the initiating event, and works backward to identify the necessary conditions.(49)

The advantage with the systems approach posited in this article is the ability to represent human behavior as part of the infrasystem, and how it is affected by feedbacks, both positive and negative. It also demonstrates the interdependencies among various subsystems, which are often interactive processes that cannot be described in unidirectional decision-tree approaches. To give a simple example, the behavior of an individual within the infrasystem will be affected by his or her prior experience. Both fault- and event-tree analyses adopt a linear logic approach, which does not capture the dynamic nature of human behavior within the infrasystem. To overcome this weakness, some researchers have adopted hybrid approaches in disaster risk analysis and management. The resulting approach can be complex and unwieldy.(50) The systems approach proposed here can capture the dynamic interactions within the infrasystem, while retaining a relative simplicity of exposition.

1.4. Choice of Case

To illustrate the general method described above, we have chosen a major flooding event experienced in southwest England during the winter of 2013/2014. In addition to being well documented, the flooding exhibits many of the characteristics typical of CHASs; it shows clear interaction among the three subsystems, a series of opposing viewpoints deriving from the actions and perceptions of the HAs, observable threats or risks, and a clear set of policy or action dilemmas, deriving from differing hypotheses about system architecture, differing valuations of system outputs, and the inevitable emergence of unwanted or unexpected effects of a system intervention aimed at achieving a particular desired effect.

1.4.1. Risk Identification within Flood Risk Management

Risk identification and assessment in flood risk management specifically is a complex process involving expertise from various disciplines and combining different data sources, models, and information. Analysts typically define flood risk as the combination of the chance of a particular event, together with the impact that the event would cause if it occurred.(51) This can be operationalized as a function of hazard, exposure, and vulnerability.(52)

Flooding highlights the importance of CHASs, since its impacts, economic costs, and risk to life are strongly dependent on human actions taken operationally both during and prior to the events themselves.(53) Indeed, the events themselves are the result of a series of human decisions taken over centuries, as exemplified in the case in hand of the flooding in Somerset, a low-lying county in the United Kingdom, in 2013.(54)

Within the field of flood risk management, risk identification and assessment is typically undertaken in four stages: (1) hazard identification and assessment; (2) exposure assessment; (3) vulnerability assessment; and (4) risk assessment.

Hazard assessment seeks to identify and evaluate the source of danger. Flooding is not a single phenomenon, but it can arise from extreme flows that exceed river capacities (fluvial flooding), intense rainfall that exceeds the capacity of drainage infrastructure (pluvial flooding), storm surges that lead to coastal flooding, and high groundwater levels or any combination of such factors.(55) A significant shortcoming of risk identification within flood risk management is the inability to consider different sources of flood hazard and their co-occurrence. These characteristics can include infrasystem variables such the depth, velocity, rate of rise, the occurrence of any pollutants, and contributing factors from the social and political subsystems. Furthermore, the characteristic that causes danger will vary among different groups, assets, and systems. There is a high degree of interaction between HAs and the physical infrasystem, producing a variety of both wanted and undesirable, planned and unexpected outcomes.

Once the source of flood risk is identified, the assessment of flood risk typically continues with an assessment of the flood hazard, and the application of computational models, which can broadly be classified as meteorological, hydrological, and hydraulic. Meteorological models aim to simulate the particular conditions that give rise to extreme rainfall or low pressures that can cause storm surges, leading to coastal flooding.(56) Hydrological models are used to simulate the amount of runoff that could be generated because of these weather conditions.(57) Hydraulic models then represent the movement and storage of water through an environment, providing information on typical depths and velocities. Such models can be used on large, global scales(58) or at fine, urban scales.(59) It is worth noting the clear emphasis placed in such studies upon the physical infrastructure variables as opposed to the role of human agency in creating and mitigating or amplifying the risks.

The next stage is to evaluate the consequences of flooding, which involves an understanding of exposure (what assets and systems are in harm's way), and their vulnerability (the extent of the damage caused if these systems are inundated). The former relies on a reliable knowledge of the location of people, assets, and infrastructure, which can be represented in geographical information systems,(60) but we note here that the primary role of the HAs is that of victims rather than being in any participatory relation. Assessing their vulnerability is complex. The vulnerability of communities to flooding requires a thorough understanding of relationships, support networks, and various intangible factors, but critically this is not carried out using explicit connection between individuals, formal and informal groups, and the risk dynamics, and is dominated by narrow considerations of the infrasystem behavior, thus underestimating the importance of both the political and social subsystems. Typically, the assessment of damage to fixed residential assets is carried out using flood damage functions that relate the characteristics of the flood (usually depth) to the damage cost for different asset types.(61)

Finally, the risk can be determined by combining these predictions of event likelihood and effect into an integrated expectation measure, normally expressed as an expected annual damage (EAD).(62)

A significant problem in flood risk identification and assessment is in understanding indirect effects that arise through the interruption of supply chains or the failure of critical infrastructure, each of which is subject to human agency. Improved assessment of these factors requires improved knowledge of the systems subject to the flooding, and the role of humans as agents. Only in recent years are researchers beginning to develop methodologies that incorporate system approaches to consider the knock-on effects on critical infrastructures.(63,64)

We will see these various roles of HAs and actors in the example case chosen, namely, the flooding events in SW England (and by extension into the Thames Valley, a prosperous area west of London).

1.5. The Somerset Levels Floods, Winter 2013/2014

1.5.1. Situation and Context

The Somerset Levels are a low-lying saucer-shaped depression of some 650 km^2 in extent in southwest England containing a few “islands” of higher ground such as the well-known Glastonbury Tor. There are several villages and small towns, containing around 800 dwellings.

The area has been farmed for many hundreds of years and has been subject to winter flooding for that entire period, the first recorded flood event being in 1607 with some 2,000 fatalities. With more intensive farming and an increase in population, the effects of flooding have been amplified in recent decades, both in terms of intensity of the floods and in their effects on the inhabitants. Storms during the winter of 2013/2014 caused extensive flooding in the Levels that, together with later flooding events in the populous Thames Valley, just west of London, precipitated emergency action on the part of the U.K. Environment Agency (UKEA) and other responsible bodies such as DEFRA, the U.K. Government Department for Environment, Food and Rural Affairs.

The Levels are drained by a number of rivers flowing into the Bristol Channel to the north, which has a notably high tidal range of some 14 m at spring tides. The tides cause diurnal hydraulic blockages that have effects back upstream. There are some tidal gates allowing gravitational draining at low tide and facilities for pumping over earth banks.

1.5.2. Brief Chronology(65–72)

22 Dec 2013	Cyclone Dirk hits the United Kingdom. Somerset Levels flooding begins.
23 Dec	Network Rail, responsible for national rail infrastructure, describes the damage to the rail network in southern England as worse than that seen during the St. Jude storm in October. Localized flooding in southern England, as the storm brought up to 60 mm of rain to the United Kingdom. Major incident declared in the region of Thames Valley. One-hundred thousand homes reported without power across southern England.
3 Jan 2014	Strong winds and high tides bring flooding to large parts of western England, Wales, and Scotland. River Parrett, a main drainage outlet, overflows. Demands for resumption of dredging.
24 Jan	Sedgemoor District Council and Somerset County Council declare a “major incident” in flooded areas as forecasters warn of more rain; 7,000 hectares in the Levels have been underwater for more than one month.
25 Jan	Trees are uprooted and structural damage caused to buildings by lightning as a heavy rainstorm hits the U.K. Midlands region.
27 Jan	Visit by Environment Secretary. PM subsequently confirms dredging will occur in Levels.
30 Jan	Figures released by the Met Office indicate southern England and parts of the Midlands have experienced highest January rainfall since records began in 1910. Military personnel prepare to help residents in flooded areas of Somerset.
3 Feb	Reports of minor looting result in mounted police being deployed.
4 Feb	HRH Prince Charles visits. Local MP raises profile by personal abuse of Head of Environment Agency.
5 Feb	Part of the sea wall carrying the railway line linking London with the west of England is washed away by a powerful storm. Thousands of homes are left without electricity. PM announces an extra £100 million will be spent U.K.-wide on dealing with the aftermath of the floods.
6 Feb	The Ministry of Defence sends around 40 Royal Marines to the Somerset Levels to help with flood protection as more storms are expected. The government also provides an extra £30 million for repairs. Local action group FLAG set up to provide a channel of communication between system inhabitants and policymakers.
8 Feb	Large areas of England and Wales under flood warnings as another storm arrives. The Somerset Levels are the worst affected area. Rail links to southwest England are again cut off by the storms.
9 Feb	Thames Valley floods. Major incident declared. Army mobilized to support.

10 Feb	Support from locally-based Royal Marines arrives at the Levels. Major conurbation of Bridgwater partially flooded. Over 600 houses flooded. Major disruptions to trains on the Bristol to Exeter main train line, a critical physical communication asset.
11 Feb	U.K. Prime Minister orders that "political bickering" should end.
21 Feb	Giant pumps from the Netherlands become effective in lowering the level in King's Sedgemoor Drain.
22 Feb	Reports of vandalization of temporary flood barriers.
26 Feb	Northmoor pumping station is installed.
27 Feb	Environment Secretary visits the Levels. Subsequent commitments to further £60m investment in pumping
27 March	Levels declared free of floods.

1.5.3. Key Human Interventions and Actors

1. The role of the U.K. Environment Agency (actor ***E***) as the conduit for and applier of funding from the central government (primarily DEFRA, actor ***G***) is critical, and it plays a key part in deciding on the relative expenditures on, for example, dredging versus pumping versus tidal barrage expenditure, both short and medium term.
2. Media (actor ***M***) including local and national radio, television, and print journalists in conjunction with local population (actor ***L***) are clearly influential in the raising of government and the general public's (actor ***P***) awareness of the situation, setting, indirectly, the short-term political agenda and influencing the long-term agenda in conjunction with ***E*** and ***G***.
3. Local farmers (actor ***F***) as a subset of ***L*** have a specific interest in soil management vis-à-vis dredging or barrage solutions. Protective of their existing farming practices, this group favors dredging solutions over others and has the support of the National Farmers' Union.
4. Disruptive elements (actor ***D***) such as the looters and vandals (February 3 and 22) have some influence over police intervention policy and practice.
5. Environment Agency and other scientists (actor ***S***) influence the quality of debate, particularly that surrounding the dredging issues.

1.5.4. Policy Issues Emerging from the Chronology

The management of such a situation, not surprisingly, is dominated by a series of policy conflicts that in retrospect (although not at the time) are relatively easy to see. Many of the policy choices inevitably center on the deployment of resources in the short term, for example, whether emergency staff (such as army personnel) should be deployed in preventive duties such as drain clearance or in humanitarian activity such as evacuation or road clearance.

There is a clear policy choice to be made over the extent to which central government funds should be deployed into an emergency, at risk of depleting the availability of such resources for future unexpected events.

The two most striking policy dilemmas in the Somerset Levels flood crisis were the clear and public disagreement over the extent to which dredging the main waterways was the key to flood control and the tension between local demands for action vis-à-vis the apparent inaction of central government. Accepted local wisdom, evidenced by years of intensive dredging, was that the key intervention for flood prevention was to keep clear the main waterways, carrying runoff from the farmlands.(73,74) There is evidence, however, that these "system inhabitants" had been "offered false hope due to the lack of science and evidence to support claims that widespread dredging alone can act as a flood prevention measure."(72) In contrast, there is significant evidence that the major cause of flooding was not the capacity of the drainage waterways so much as the effect of tidal range, increasing the blocking effect at the outlet of these waterways, indicating a preferred policy of expenditure on tidal barriers and pumping.(72) Nevertheless, social pressures from inhabitants resulted in immediate dredging becoming part of the 20-year action plan. Moreover, "[d]redging of the rivers Tone and Parrett had the potential to cause increased flood risk downstream, in particular to Bridgewater. The increased confluence downstream combined with high tides were expected to cause increased water depths, and possible overbank flow at points where not previously experienced."(72)

In respect of the policy dilemma over funding, there are two components. First is the straightforward securing of funding, whereby the Environment Agency was accused of failing to secure funding from DEFRA. This was, understandably, the basis of attempted political escalation by the inhabitants and FLAG, the local action group. Second was the effect of local feeling that it was only when the Thames Valley became flooded in February, that action on the ground in the Levels became sufficiently high on the policy agenda.

With the benefit of hindsight, it is tempting to think that these dilemmas or policy conflicts should have been obvious to the system owners, be they disaster managers or policymakers, but the chronology of the Floods shows that, rather than being identified at an early stage in the development of the disaster, they emerged unexpectedly at the point of conflict.(75) A good example of this is the (perhaps unreasonable) irritation of Somerset Levels inhabitants that "action was only taken when the Thames Valley flooded." If this had been identified as a potential cause for conflict, action could have been taken in the social and policy subsystems to attenuate the feeling of inequity and avoid significant press and media involvement of a negative nature.(76,77)

1.6. Modeling Approach: QPID

In strategic systems studies, there is a small set of existing techniques to clarify the interactions of HAs with the equivalent of our infrasystem, the most common being SSM(21) and SODA.(78) While these have the advantages of familiarity and indeed inform an extensive body of praxis on which to draw, both have the disadvantage in this application of a dislocation from the specific processes of the system in focus. Since, in our view, the process of risk identification needs to be closely related to the specific system processes (almost certainly using such broad methods as SSM as a precursor in system design) we adopt the methodology of system dynamics in its qualitative form(79,80) and in particular the methodology of QPID,(44–46) which attaches HAs, by elicitation from informants in focus groups, to specific system processes.

The process is a simple one. Fig. 1 shows a typical dynamic loop extracted from an influence diagram using the method detailed previously.(44) It represents a particular chain of causality where the drainage capacity (here voiced as *capacity for runaway*) is affected by the ability of the farmland to absorb water (*surface porosity of farmland*). On farmland, the soil is often compressed by heavy farm machinery or livestock, which reduces the porosity. Consequently, the infiltration capacity is decreased and leads to poor drainage capacity. The effects of "hardscape," of significance in more urban environments, are of minimal effect at this stage of development of this largely rural context, although over a longer timescale they may become of importance, to the extent that urban development of the area is allowed. The loop is closed by the linkage between the propensity of the land to flood (voiced as *duration of flooding*) and its desirability for agriculture (*fraction of soil to agriculture*). It must be stressed that Fig. 1 captures only one of a series of interconnecting and often conflicting mechanisms, which, working in conjunction, result in the overall system outputs.

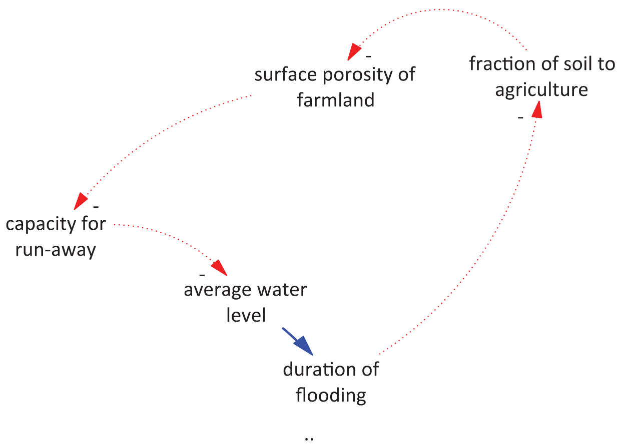


Fig. 1. Typical loop extracted from ID (showing effects of reduced surface porosity dynamics).

The QPID extension deployed here attaches agents and groups of agents to the causal arrows constituting the dynamic loops, again through expert focus groups. Although in some cases there will be many hundreds or even thousands of dynamic loops (the topology of loops being combinatorial with respect to the number of variables), the process of attaching coded agents to the causal arrows is less onerous, since the number of causal links in a diagram is at worst polynomial (N^2) with respect to the number of variables (N).

1.6.1. Analysis of QPID Diagrams

The process of analysis of the risk contribution of the HAs proceeds as follows:

(1) Selection of significant dynamic loops for examination, together with the desired behavior of that loop as judged by the system owner
(2) Attribution of HAs to each arrow of each loop chosen for analysis

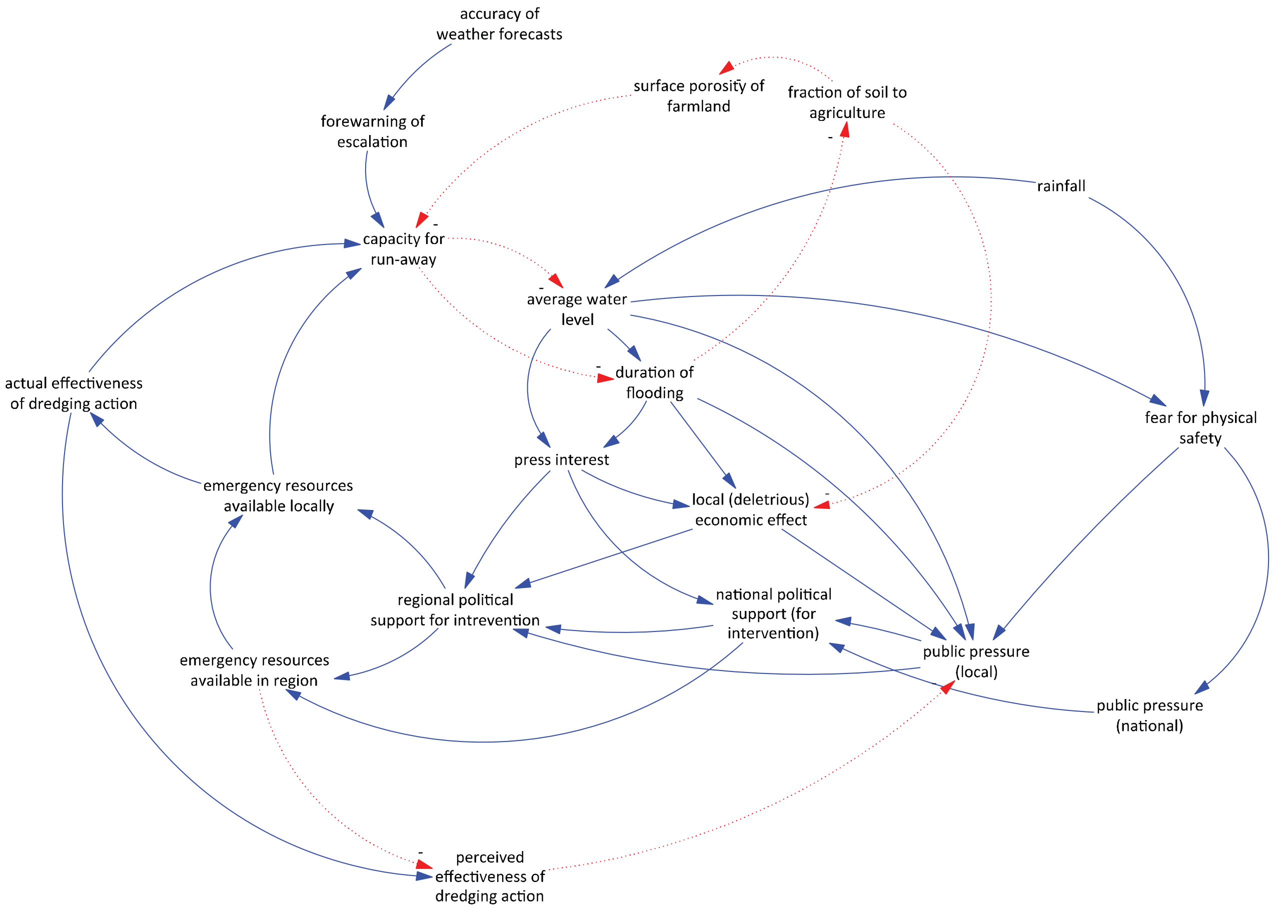


Fig. 2. Full ID for Somerset Levels.

(3) Establishment of the relation of each HA to the process or processes underlying the causal connection implicit in the arrow
(4) Establishment of the motivation of each HA in that relation
(5) Establishment of the capacity of the agent to disrupt or fail to support the system owner's motivated outcome
(6) Declaration of the threats and risks carried by the agents in respect of the arrow
(7) The options for risk mitigation or management associated with that agent (if any)
(8) The appropriate actions by the system manager/owner for risk control
(9) The resource implications of those actions

An additional practical step is the identification of residual risks remaining after mitigation or control action has been completed.

We illustrate the process by an analysis of part of an extensive QPID diagram of the flooding in late 2013–early 2014 of the Somerset Levels in the southwestern United Kingdom.

1.7. Illustrative Example—Flood Threat to the Somerset Levels 2013/2014

Fig. 2 shows the full ID of the illustrative example of the flood threat to the Somerset Levels, a low-lying flood plain situated in the southwest of the United Kingdom, which, during winter 2013/2014, was subject to catastrophic flooding during an episode of extreme rainfall and storm conditions that caused severe resource demands over the entire United Kingdom. The severity of the situation caused inevitable local, regional, and national political conflicts of policy, press interest, and a combination of socially defined feelings of isolation, economic dysbenefit, and personal risk,

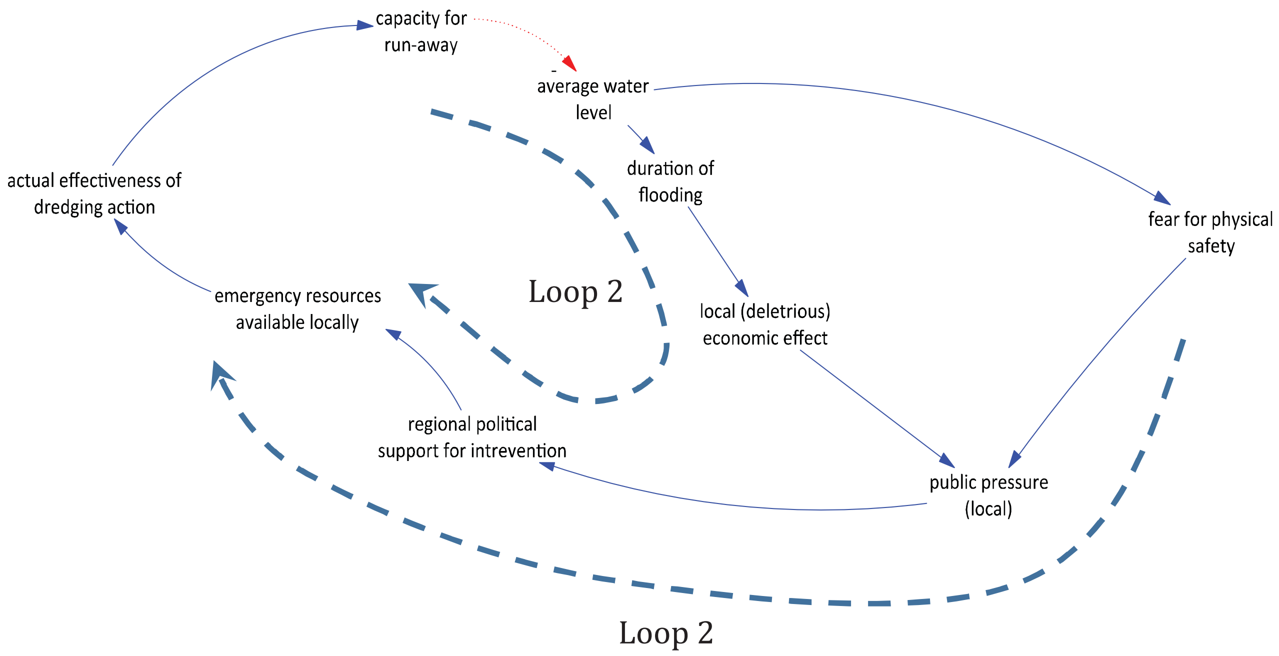


Fig. 3. Loops 2 and 3.

illustrating the relevance to the risk identification and management task of the three submodels of Fig. 1, each of which is represented in the full QPID of Fig. 2.

The influence diagram of Fig. 2, although relatively uncomplicated in system dynamics terms (many IDs comprise upwards of 50 variables), captures key dynamics inherent in the case description, such as the long-term effects of soil management, medium-term effects of run-away capacity management, and short-term effects of political pressures resulting in the release of centrally held resources, such as pumps and manpower.

Fig. 1 shows the soil management loop. As the *fraction of soil to agriculture* (and hence the degree of soil compaction) increases (reducing the extent of open, porous surface area) the *capacity for run-away* decreases (the arrow is dotted, indicating negative correlation), not because of any effect of the conveyance of relief water channels, but because of the integrated, distributed effect of a reduction in the ability of the land surface to absorb and gradually release rainfall. As a result, the *average water level* increases, and because the *duration of flooding* year on year increases, the propensity of farmers to put land to agriculture will decrease. The loop of Fig. 1, then, is a goal-seeking loop, in that an arbitrary increase in one variable (say the amount of land put to agriculture) will produce an effect that ripples round the causal loop, but that dies out. It must be remembered that there will be exogenous factors also at play, which will affect the variables and hence the loop behavior. For example, the motivation of farmers to put unused land to agriculture will be affected by the economic pressures on them. In addition, from an overall system perspective, the behavior of loops such as that of Fig. 1 cannot be understood in isolation, since, as examination of Fig. 2, the full ID, will show, there are other dynamic mechanisms that affect its component variables, for example, through the variable *capacity for runaway*, which can, in the short term at least, be increased by emergency pumping and (although contentiously) by dredging.

We can see this in the two loops contained in Fig. 3.

The left-hand loop 2 describes a medium-term effect, whereby, as the flooding of the region increases in duration, the *local (deleterious) economic effect* increases. Inhabitants begin to lose agricultural productivity, trade decreases because of the difficulty of travel, and so on. As a result, *public pressure (local)* rises. Residents demand action, which raises the *regional political support for intervention*; politicians react to public pressure. To the extent that the regional authorities have access to deployable resources and *emergency resources available locally*,

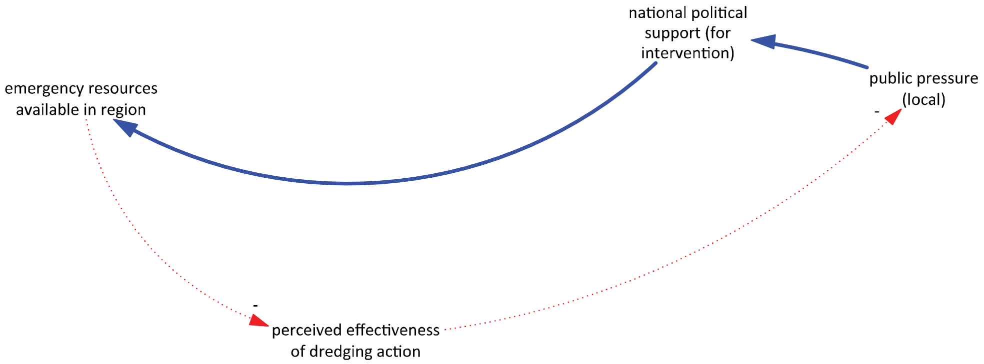


Fig. 4. Loop 4 accelerating effect of local disaffection.

they are deployed, increasing the *capacity for runaway* (e.g., by improved pumping) and this reduces the average water level, eventually assuaging the effects on the local economy.

Loop 3 (also in Fig. 3) captures a similar mechanism, linking human agency with the infrasystem of drainage and water levels, but is of a much shorter time constant in that the rise of public *fear for physical safety* will be faster than the corresponding variable in loop 2, the *local (deleterious) economic effect* of sustained flooding.

Similar loops that link the public reaction to the provision of resources through the local, regional, and national political mechanisms can be extracted from Fig. 2.

Two striking factors emerge from consideration of the Somerset Levels case, namely:

- The effect of continuing insistence by inhabitants that the optimal palliative measure was dredging in the face of expert analysis to the effect that the main causes of water level rise were increased agricultural use exacerbated by the downstream presence of an exit blockage due to the huge tidal range (>14 m at spring tide) of the Bristol Channel.
- The (perceived) slowness of response to the extended crisis in the Levels until the Thames Valley, closer to the seat of power in London, experienced similar floods. Suddenly, the political importance of the weather events increased, making available substantial emergency and medium-term resources, not only in the Thames Valley but in the Levels as well.

The first of these prominent effects can be seen in loop 4 (Fig. 4).

Here we see that as *public pressure (local)* increases, *national political support for intervention* rises (inhabitants would attest that the rise was not sufficiently fast). As a result, emergency resources (pumping and humanitarian relief) were applied. Counterintuitively, however, because of the existing unchallenged assumptions that the solution was dredging, the appearance of the pumps was seen as "evidence" that the dredging activity was insufficient (since more pumps were needed). Hence public disaffection increased, putting more pressure on national authorities. The political conversation remained distorted by the presence of the assumption of the efficacy of dredging vis-à-vis longer-term and downstream ameliorations.

Fig. 5 (containing loop 5) throws some light on the effect of the Thames Valley floods, which (at least in the eyes of the inhabitants of the Levels) precipitated a long overdue response.

The Thames Valley events and the fast-rising water levels, highly visible at the time on television and in print media, created a feeling of *fear of physical safety* nationally (not least because the events took place within commuting distance of the U.K. Parliament). This raised the national political profile of flooding in general and hence of *national political support for intervention* in the preexisting Levels problem. Emergency response teams were provided not only to the Thames Valley, but to the Somerset Levels as well. To the extent that the interventions were effective in reducing water levels, (national) public concern fell and political pressure was reduced.

We can see, then, that the ID of Fig. 2 contains the significant dynamics to be drawn from the earlier case-based description of the Levels flooding events. We now proceed to an agent-based analysis of this model.

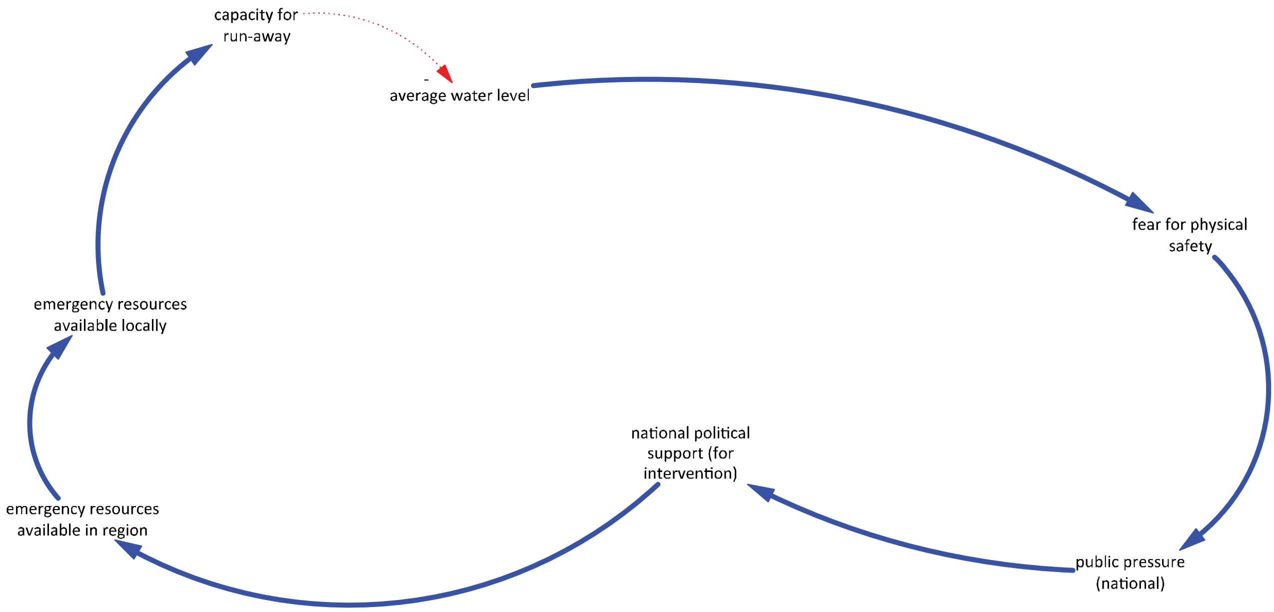


Fig. 5. Loop 5: effect of national pressure.

1.8. HA Analysis

Having identified the significant dynamic loops in the normal manner for a qualitative SD model (i.e., by inspection, possibly supported by additional numerical modeling), the QPID analysis(44) then attaches agents to the arrows of each loop. We use as an example loop 01 in Fig. 2, which captures the effects of land use versus short-term flooding effects through surface porosity degradation. This loop is strong in effect but rather slow in action, in that the transfer of land from fallow ground (or set-aside) to agricultural use takes place over a season at minimum.

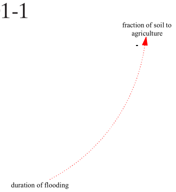
Fig. 3 contains a key to the agents who affect the strengths of the arrows constituting the dynamic loop of Fig. 2, and hence the overall system output.

It should be noted that the attachment of an agent to an arrow denotes that the agent in question has a direct influence over the strength or polarity of the connection. Sometimes, that influence can be very direct (for example, the farmer ***F*** in the arrow *duration of flooding →fraction of soil to agriculture*) or indirect (for example, the agronomist ***A*** on the same arrow giving authoritative advice to that farmer on land usage). Moreover, agents may have different strengths of influence one from another, and may have different strengths of effect in different parts of the system.

The attachment of agents to causal arrows is often more conveniently done in a tabular fashion as in the example of Table III for the loop of Fig. 6. The tabulation of risks seen in Table III is performed for all significant loops in the ID. This can be a time-consuming process, but in practice no more so than the time available, since loops can be prioritized according to speed of action and power (by which we mean the degree of influence of a particular loop upon significant system effect, this varying from stakeholder to stakeholder). The order of priority will, in general, be STRONG + FAST, WEAK + FAST, STRONG + SLOW, and lastly SLOW + WEAK. In some cases, simulation can be used to mobilize whatever quantitative data are available, but general managerial practice has shown that it is relatively easy to identify the appropriate loops for analysis by inspection and through tacit knowledge of the significant systems dynamics.

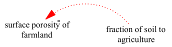
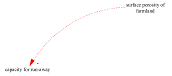
Completion of the table follows by consideration of each agent in respect of his or her connection with a specific causal element or arrow. Each arrow is taken in turn, and the motivations and capacity of each potential actor considered to specify the actor's role in respect of that particular arrow, bearing in mind that an actor's capacity to action can be very different in one mechanism from another. Generally, an actor's system-level motivation will remain

Table III. Worksheet for One Dynamic Loop (Loop 01)

Causal Arrow from Loop 01	Agents + Nature of Relation	Motivation of Agent	Capacity to Affect	Risk(s)	Mitigation/Control
01-1 	***F = Farmers*** ***Farmers have control over land usage under planning constraint***	Economic; Likely to favor shorter-term cash flow against longer-term issues	Can determine crop planting and irrigation regimes, thereby affecting run-off dynamics	***Insistence of farmers to pursue individual revenue at cost to surface conditions of farmland***	01-1- F-1 Appeal to common benefit argument through press, NFU, and gov't pamphlets 01-1-F -2 Advocacy of specific farming practices to increase porosity of surface soil 01-1-F-3 Advocacy of danger to long-term income
	P = Planners ***Control usage of land***	Balancing of land use for overall public benefit	Able to apply national and regional planning legislation under penalty for noncompliance but subject to public pressure from inhabitants under this	***Failure of Planning Authority to police zoning needs consistent with flood management***	01-1-P-1 Ensure clarity of national and regional policy to Planning Authority
	A = Agronomists ***Advise on crop and land use and farming practice***	Maximization of productivity of farmland	Advisory function to farming bodies such as large farms and NFU	***Tendency of agronomists to stress productivity over environment***	01-1-A-1 Lobby agronomists involved in Somerset Levels on environmental issues 01-1-A-2 Hold mini-conference on holistic planning problem
	N = National Farmers' Union (NFU) ***Represents farmers' interests***	Maintenance of effectiveness of NFU in the minds of members	Collective representation allows access to national and regional policymakers	***Insistence of NFU to safeguard members' revenue; tendency to advocate short term measures***	01-1-N-1 Obtain press coverage to point out myopia of a revenue-driven approach

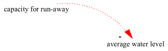
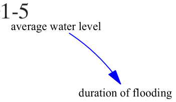
(*Continued*)

Table III (Continued)

Causal Arrow from Loop 01	Agents + Nature of Relation	Motivation of Agent	Capacity to Affect	Risk(s)	Mitigation/Control
01-2 	***F = Farmers*** ***Farmers determine ratio of set-aside usage to productive usage***	Economic; Likely to act to maximize short-term income	Limited; Set-aside will be determined by E.U. grant availability; Some capacity to choose planting regimes	***Farmers plant crops on (short-term) economic basis alone***	01-2-F-1 Mobilize current research on differential run-off effects for various plantings 01-2-F -2 Advocacy of specific farming practices to increase porosity of surface soil
	P = Planners ***Control usage of land***	Balancing of land use for overall public benefit	Limited; Planners must act under extant legislation	***Planning allows indiscriminate use under zoning of "agricultural use"***	01-2-P-1 Lobby Planning Authority to differentiate various agricultural usages in zoning
	A = Agronomists ***Advise on crop and land use and farming practice***	Maximization of productivity of farmland	Advisory to large farms and NFU; Has capacity to present a balanced viewpoint *vis-à-vis* flood measures	***Insensitivity of agronomists to consequential hydrological effects***	01-2-A-1 Set up conference to present hydrological modeling and current crop research
	H = Hydrologists ***Have authoritative knowledge of relation between hydrological factors***	Professional integrity and reputation	Scientific community advises government and planning authorities	***Hydrologists fail to see connection between crop plantings and runoff***	01-2-H-1 Set up conference to present hydrological modeling and current crop research
	N = NFU ***Represents farmers' interests***	Maintenance of effectiveness of NFU in the minds of members	Collective representation allows access to national and regional policymakers	***Union lobbies for income-driven planting and freedom of usage***	01-2-N-1 Prebrief press on planting/usage options for farmers
01-3 	***F = Farmers*** ***Farmers have control over resource application for drainage on their land***	Economic; Likely to favor shorter-term cash flow against longer-term issues.	Very strong; Application of funds is entirely discretionary on individual farmers, but they must also maintain existing drainage systems	***Farmers avoid cost of proper drainage***	01-3-F-1 Lobby for penalties for failure to maintain drainage 01-3-F-2 Make farmers aware of economic and legal consequences of failure to maintain drainage

(*Continued*)

Table III (Continued)

Causal Arrow from Loop 01	Agents + Nature of Relation	Motivation of Agent	Capacity to Affect	Risk(s)	Mitigation/Control
	A = Agronomists ***Advise on crop and land use and farming practice***	Maximization of productivity of farmland	Limited to advising among available viable crop choices	***Agronomists concentrate overly on crop productivity***	01-3-A-1 Create research-based arguments for longer-term perspective
	H = Hydrologists ***Have authoritative knowledge of relation between hydrological factors***	Professional integrity and reputation	Limited, but can advocate importance of surface porosity/run-off arguments	***Hydrologists fail to advocate for proper drainage on farmland***	01-3-H-1 Set up conference to present hydrological modeling and current crop research
01-4 	***P = Planners*** ***Control usage of land***	Motivated to provide robust infrastructure	Strong; Can condition policy on infrastructure issues such as channel capacity	***Need for immediate drainage ignored***	01-4-P-1 Ensure planning rules are appropriately drafted and monitored *See* also 01-4-H-1
	H = Hydrologists ***Have authoritative knowledge of relation between hydrological factors***	Professional integrity and reputation	Strong; Can use authoritative research to determine infrastructure design	***Effectiveness of immediate drainage low***	01-4-H-1 Ensure good design rules are implemented through planning
01-5 	***P = Planners*** ***Control usage of land***	Motivated to provide robust infrastructure	Strong; Can condition policy on infrastructure issues such as channel capacity and tidal blockages	***Allow downstream drainage to be low in effectiveness***	01-5-P-1 Monitor institutional planning applications for compliance 01-5-P-2 Instate regional drainage plans
	H = Hydrologists ***Have authoritative knowledge of relation between hydrological factors***	Professional integrity and reputation	Strong; Can use authoritative research to determine infrastructure design		01-5-H-1 Instate regional drainage plans

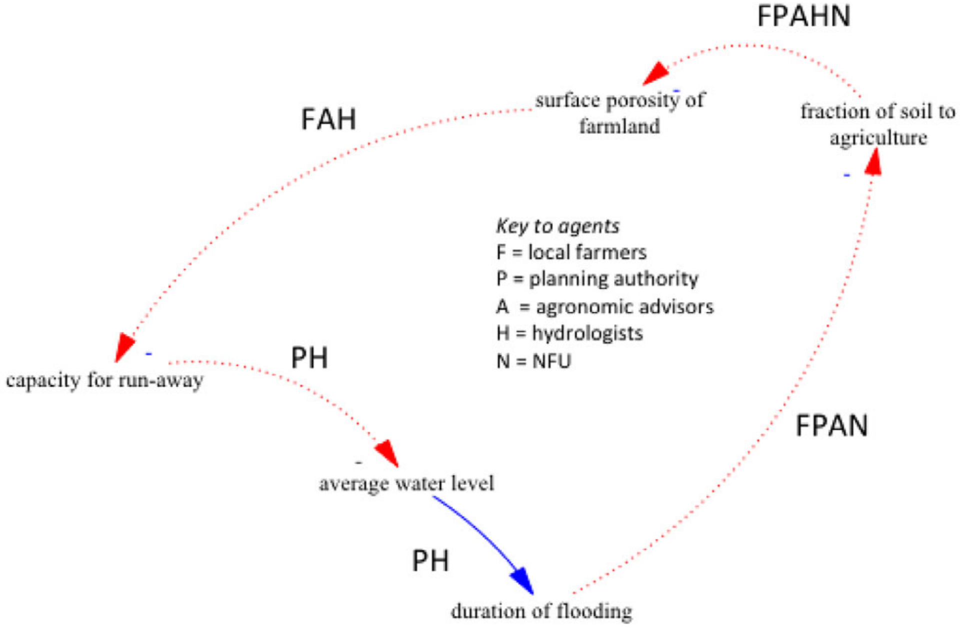


Fig. 6. Dynamic loop with agents attached.

constant from one mechanism to another, although the local interpretation and reification of that motivation in the specific mechanism may vary.

- Column 2 captures the relation of the agent to the causal mechanism, i.e., the nature of the contribution to the mechanisms. For example, in Table III row 1 the farmer (***F***) has control over the usage of the land, but of course is limited in this by planning and other legal and nonlegal constraints. Some crops are forbidden, some are uneconomic, some are contributory to run-off dynamics, some are not.
- Column 3 expresses the perceived motivation or motivations of the agent in respect of the particular causal mechanism under consideration. It is this adjacency between the agent and the component of the system operation, as distinct from any aggregated judgement, that allows the proposed method to identify specific risk and threat mechanisms. The motivations may, of course, be multiple, even apparently conflicting, reflecting, perhaps, some moral hazard or straightforward conflicts of objective.
- Column 4 details the extent to which the actor in question can affect that particular causal link, often elucidating the mechanism of effect. For example, in the case of ***F*** in row 1 of Table III, the decision to plant particular crops, will, in part, determine the run-off characteristics, the irrigation regime needed, and, to some extent, the soil structure itself. It should be noted that the capacity to affect is limited to the particular causal mechanism (i.e., the arrow) in question. Any potential for ***F*** to affect other parts of the system (e.g., downstream hydraulic effects through effective ditch maintenance) will appear in that part of the system diagram relevant to that mechanism. Again, the specificity of the approach allows precise threat and risk identification.
- Column 5 identifies the specific risks emerging from the content of columns 1 to 4. The motivation of the actor, coupled with the capacity for effect, leads to identification of a particular risk, here that the farming community will act so as to maintain shorter-term economic return rather than adopting a more strategic view. This is not to say that this risk will be reified, because the mitigating and control mechanisms of column 6, and indeed other system mechanisms acting to moderate such an approach, may come into play. Nevertheless, in terms of risk identification, the interaction of actor with mechanism under assumptions of motivation and subject to limitations of effect lead to clear HA risk specification.

Table IV. Key Dilemmas in the Somerset Levels Case

Topic	Thesis	Antithesis	Actors
Soil management vs. dredging(72)	Flooding is caused by poor soil management	Flooding is caused by lack of free drainage through the Tone + Parrett	Farmers Environmentalists DEFRA[a]
Dredging vs. long-term area management(72)	Flooding is caused by backup from tidal effects exacerbated by climate change	Flooding is caused by lack of free drainage through the Tone + Parrett	Farmers Planners DEFRA
Resource allocation	Resources should be deployed to Somerset Levels	Resources should be deployed to Thames Valley	DEFRA Press House of Commons (HoC)
Sources of funding	Local funding	Government funding	Local government HoC EA[b] DEFRA
Long vs. short term	Long-term savings	Short-term investment	Local government EA DEFRA

[a] (U.K.) Department for the Environment, Food and Rural Affairs.
[b] (U.K.) Environment Agency.

1.9. Effectiveness of Procedure

The benefit of the process encapsulated in Table I is in its discipline and in the specific attribution of the HA's motivation and capacity to specific system mechanisms. An explicit system description is deployed, leading to declared assumptions of the key system dynamics.(1) The key step in terms of identifying the risks either deriving from or substantially controlled by the HAs is in the exhaustive declaration of each agent's interest in the step-by-step operation of each loop. This is undoubtedly onerous; establishing a viable ID for a typical CHAS requires around three sessions of about three hours each for a team of, for example, four informants and a facilitator. Subsequent loop analysis takes about one day of a single analyst's time. The tabulation of risk (*qua* Table I) requires around two hours for each loop with the attendance of sufficient representation to allow well-founded conjectures to be made about the motivations and likely behavior of absent stakeholders. Thus, if we assume around 10 significant loops in the ID, a typical initial human agency risk analysis for a CHAS would entrain some 170 man-hours, or around 20 man-days. This is entirely consistent with the wholly appropriate but substantial resource allocated to risk and threat identification by conventional means.

Against this must be measured the utility. The ability to identify in an auditable way the risks involved in a situation, particularly in advance of occurrence of a crisis, is potentially of considerable, albeit inestimable, benefit. Of particular benefit to decisionmakers is the identification of the implications of action dilemmas, by which we mean multiple options for action, each of which presents obvious and planned benefits but unexpected, usually undesirable disadvantages. The decisionmaker must then choose between these policy options (usually, but not always presented in pairs). The ability to make sound conjectures about these ancillary outcomes is valuable in its own right, particularly regarding unexpected outcomes. It is a strength of the system approach to risk that it is more likely to adumbrate unexpected risks than the essentially linear causal analysis of conventional approaches.

A good example of a simple dilemma is shown in the present case where we compare the effects of loops 2 (or 3) and 4. In the former case (Fig. 3), the effect of emergency provision is as anticipated; pumping machinery arrives, the water level drops, and, equivalently, economic trading is reestablished (loop 2) or, more dramatically, the inhabitants of the Levels feel less threatened by the flooding (loop 3). What is of value to the risk manager of the situation, however, is the recognition of the less desirable dynamics of loop 4 (Fig. 4). Because of the immanent assumptions of the inhabitants about the need for dredging as the primary solution of the problem, the arrival of the emergency measures is seen as supporting the case that dredging is insufficient, for (they argued) if the dredging is sufficient, why would emergency pumping equipment be needed?

Other dilemmas in the Levels case are shown in Table IV.

Examples of such action dilemmas occur in the management of many CHASs. They are, for example, characteristic of the class of problems known as reputation crisis management where, as in the case of the well-known Toyota product failure of 2009, a series of unexpected outcomes can emerge from what, at the time, seem perfectly reasonable responses to events. The unexpectedness of the outcomes in the Toyota case, as in the case of the flooding reported here, came primarily from human intervention.

This human intervention is not always based on a rational foundation, but it does us no good as managers of CHASs to reject bounded, localized, or even defective rationality on the part of the system inhabitants any more than it helps to bemoan the limits presented by laws of nature, geography, or the inevitability of the passage of time. In managing CHASs an awareness of the possibility of dilemmas arising, of the possible mixed effects of unconsidered intervention, and, above all, the presence of human-derived risks seems a wise insurance against exacerbating rather than improving the crisis. The human agency analysis presented here is of some assistance in mobilizing system knowledge in identifying dilemmas and in addressing the sources and consequent mitigation of human-derived risk.

1.10. Extensions to the Procedure and Future Work

An extension to the approach described here would be to include more explicitly the effect of time delays in the operation of the causal effects captured in the ID. This is common practice in SD work,(44) with the convention (in qualitative IDs) that a causal link subject to significant delay in its operation has a Δ sign attached to it.(81) This is a useful convention and indeed consideration of the speed of operation of a dynamic mechanism is of importance in two respects. The first is the rather obvious observation that its consideration allows a potential policy to be assessed as to the timeliness of its response; this allows a judgment to be made, particularly in time-dependent crisis situations, whether the effect desired will be achieved in an acceptable timescale. The second respect is that consideration of the time constant of operation of a dynamic mechanism under consideration for policy attention serves, together with the predicted magnitude of its effect, as a distinguishing factor for whether that mechanism can be considered strategic *vis-a-vis* operational. This allows a prioritization of response considerations. It is a general view that the ordering of treatment of dynamic mechanisms should be *Fast+Strong*: *Slow+Strong*: *Fast+Weak*: *Slow+Weak*,(44) and under the common constraint of time pressure in disaster planning, such a prioritization throws up the more powerful and timely action responses to the exigencies of the (now ordered) dynamic mechanisms.

Perhaps surprisingly, at least in its qualitative form, the assessment of the speed of operation of a particular dynamic mechanism is relatively easy, so long as the constructor of the ID has sufficient holistic appreciation of the system in focus. This is implicit in the content of Table III, but could be included as an extra column.

Issues of complacency, deliberate delay (including resource unavailability), and information delays including time to decision or process delays can also be incorporated in the overall consideration of time constants in this way.(81) It should be noted, however, that the representation of time constant of operation and information delays are notoriously problematical in quantitative representations.(79)

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