Modeling Multi-Hazard Disaster Reduction Strategies with Computer-Aided Morphological Analysis

Tom Ritchey
Swedish Defense Research Agency
ritchey@foi.se

ABSTRACT

Disaster Risk Management (DRM) is a multi-dimensional problem complex requiring knowledge and experience from a wide range of disciplines. It also requires a methodology which can collate and organize this knowledge in an effective, transparent manner. Towards this end, seven specialists from the social, natural and engineering sciences collaborated in a facilitated workshop in order to develop a prototype multi-hazard disaster reduction model. The model, developed with computer-aided morphological analysis (MA), makes it possible to identify and compare risk reduction strategies, and preparedness and mitigation measures, for different types of hazards. Due to time constraints, the model is neither complete nor accurate – but only represents a proof-of-principle. The workshop was sponsored by the Earthquake Disaster Mitigation Research Center (EDM) in Kobe, in January, 2005

Keywords

Disaster risk management, multi-hazard disaster reduction, morphological analysis.

INTRODUCTION

Disaster risk management (DRM) has been defined as “a systematic process that produces a range of measures associated with hazard mitigation, emergency preparedness, impact response and disaster recovery, and which contributes to the safety of communities and the environment; and at the same time parallels risk management and good management practices” (Britton 2005). It also emphasizes pre-disaster, not post-disaster measures, a combination of “top-down” and “bottom-up” thinking, and linking mitigation with development, all of which requires a multi-hazard or all-hazard approach (Mattingly 2002).

Multi-hazard DRM is a complex problem area requiring expert knowledge and much practical experience in a wide range of disciplines. It also requires a methodology which can collate and organize this knowledge through a participatory dialogue process. Towards this end, seven specialists from the social, natural and engineering sciences participated in a facilitated workshop employing a novel modeling method called general Morphological Analysis (MA). The workshop produced a prototype multi-hazard disaster reduction model which allows users to compare different hazards in terms of risk reduction strategies and adequate planning, preparedness and mitigation measures.

The workshop, sponsored by the Earthquake Disaster Mitigation Research Center (EDM) in Kobe, took place in conjunction with the World Conference on Disaster Reduction (Kobe) in January 2005.

This paper will begin with a discussion of some of the methodological problems confronting complex, non-quantified modeling as applied to threat assessments and strategy analysis. This is followed by a presentation of the fundamentals of the morphological approach. Finally, the prototype multi-hazard disaster reduction model will be described.

METHODOLOGICAL BACKGROUND

Modeling societal threats and disaster reduction strategies presents us with a number of difficult methodological problems. Firstly, many of the factors involved are not meaningfully quantifiable, since they contain strong social, political and cognitive dimensions. This means that traditional quantitative methods, mathematical modeling and simulation will not suffice.

Secondly, the uncertainties inherent in such problem complexes are in principle non-reducible, and often cannot be fully described or delineated. This represents even a greater blow to the idea of causal modeling and simulation.

Finally, the creative process involved in such studies is often difficult to "trace" – i.e. we seldom have an adequate "audit trail" describing the iterative process from problem formulation, through alternative generation to specific solutions or conclusions. Without some form of traceability, we have little possibility of scientific control over results, let alone reproducibility.

An alternative to mathematical modeling is a form of non-quantified modeling relying on "judgmental processes" and internal consistency, rather than causality. Causal modeling, when applicable, can – and should – be used as an aid to judgment. However, at a certain level of complexity (e.g. at the social, political and cognitive level), judgment must often be used, and worked with, more or less directly. The question is: How can judgmental processes be put on a sound methodological basis?

Historically, scientific knowledge develops through cycles of analysis and synthesis: every synthesis is built upon the results of a proceeding analysis, and every analysis requires a subsequent synthesis in order to verify and correct its results (Ritchey, 1991). However, analysis and synthesis – as basic scientific methods – say nothing about a problem having to be quantifiable.

Complex social-technical systems and policy fields can be analyzed into any number of non-quantified variables and ranges of conditions. Similarly, sets of non-quantified conditions can be synthesized into well-defined relationships or configurations, which represent "solution spaces". In this context, there is no fundamental difference between quantified and non-quantified modeling.

Morphological analysis – extended by the technique of internal "cross consistency assessment" (CCA, see below) – is a method for rigorously structuring and investigating the internal properties of inherently non-quantifiable problem complexes, which contain any number of disparate parameters. It encourages the investigation of boundary conditions and it virtually compels practitioners to examine numbers of contrasting configurations and policy solutions.

MORPHOLOGICAL ANALYSIS

Morphological analysis (MA) was developed by Professor Fritz Zwicky – the Swiss astrophysicist and aerospace scientist based at the California Institute of Technology (CalTech) – as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes (Zwicky 1969, Zwicky & Wilson, 1967).

Zwicky applied this method to such diverse tasks as the classification of astrophysical objects, the development of jet and rocket propulsion systems and the legal aspects of space travel (Greenstein and Wilson, 1974). More recently, morphological analysis has been extended and applied by a number of researchers in the U.S.A and Europe in the field of futures studies, policy analysis and strategy modeling (Coyle *et.al.*, 1994; Rhyne 1995; Ritchey 1997, 2003; Stenström & Ritchey 1999; Eriksson & Ritchey 2000). The method is currently experiencing somewhat of a renaissance, not the least because of the development of small, fast computers and flexible graphic interfaces.

The method begins by identifying and defining the most important parameters (dimensions) of the problem complex to be investigated, and assigning each parameter a range of relevant "values" or conditions. This is done in natural language. A morphological field is constructed by setting the parameters against each other in an n-dimensional configuration space (see Figure 1, below).

If a morphological field is small enough, one can examine all of the configurations in the field, in order to establish which of them are possible, viable, practical, interesting, etc., and which are not. In doing so, we mark out in the field a relevant "solution space". The "solution space" of a Zwickian morphological field consists of the subset of configurations, which satisfy some criteria -- usually the criteria of internal consistency.

However, a typical morphological field can contain between 50,000 and 5,000,000 formal configurations, far too many to inspect by hand. Thus, the next step in the analysis-synthesis process is to examine the internal relationships between the field parameters and "reduce" the field by weeding out all mutually contradictory conditions.

This is achieved by a process of cross-consistency assessment: all of the parameter values in the morphological field are compared with one another, pair-wise, in the manner of a cross-impact matrix (Figure 2). As each pair of conditions is examined, a judgment is made as to whether – or to what extent – the pair can coexist, i.e. represent a consistent relationship. Note that there is no reference here to causality, but only to internal consistency.

There are two types of inconsistencies involved here: purely logical contradictions (i.e. those based on the nature of the concepts involved); and empirical constraints (i.e. relationships judged be highly improbable or implausible on empirical grounds). (Normative constraints can also be applied, although these must be used with great care.)

This technique of using pair-wise consistency relationships between conditions, in order to weed out internally inconsistent configurations, is made possible by a principle of dimensionally inherent in the morphological approach. While the number of configurations in a morphological field grows exponentially with each new parameter, the number of *pair-wise relationships between conditions* grows "only" as a quadratic polynomial – more specifically, in proportion to the triangular number series. Naturally, there are practical limits reached even with quadratic growth. The point, however, is that a morphological field involving as many as 100,000 formal configurations can require no more than few hundred pair-wise evaluations in order to create a solution space.

When this solution space (or outcome space) is synthesized, the resultant morphological field becomes a flexible model, in which anything can be "input" and anything "output". Thus, with computer support, the field can be turned into a laboratory with which one can designate one or more variables as inputs, in order to examine outputs or solution alternatives (see Figure 3, below).

The morphological approach has several advantages over less structured approaches. It seeks to be integrative and to help discover new relationships or configurations. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different parameters within the problem space. The method also has definite advantages for scientific communication and – notably – for group work. As a process, the method demands that parameters, conditions and the issues underlying these be clearly defined. Poorly defined parameters become immediately (and embarrassingly) evident when they are cross-referenced and assessed for internal consistency. The method does, however, require strong, experienced facilitation.

MULTI-HAZARD DISASTER REDUCTION MODEL

The idea behind the multi-hazard disaster reduction model was to make it possible to identify and compare risk reduction strategies, and preparedness and mitigation measures, for different types of disasters. This would allow us to identify synergies or disparities in disaster reduction methods as concerns different types of hazards, which may be concurrent. It would also give us a common conceptual framework and terminology over a wide range of disaster reduction issues.

The development of the model began with the process of identifying and listing the most important parameters or variables of the problem complex. The working group identified the following eleven parameters:

- Types of hazards
- Principle risk reduction strategies
- Root causes of vulnerability
- Adequate knowledge required
- Adequate planning measures
- Adequate mitigation measures
- Adequate preparedness measures
- Legal/institutional frameworks needed
- Dynamic negative pressures
- Dynamic positive pressures
- Unsafe physical conditions & practices affected

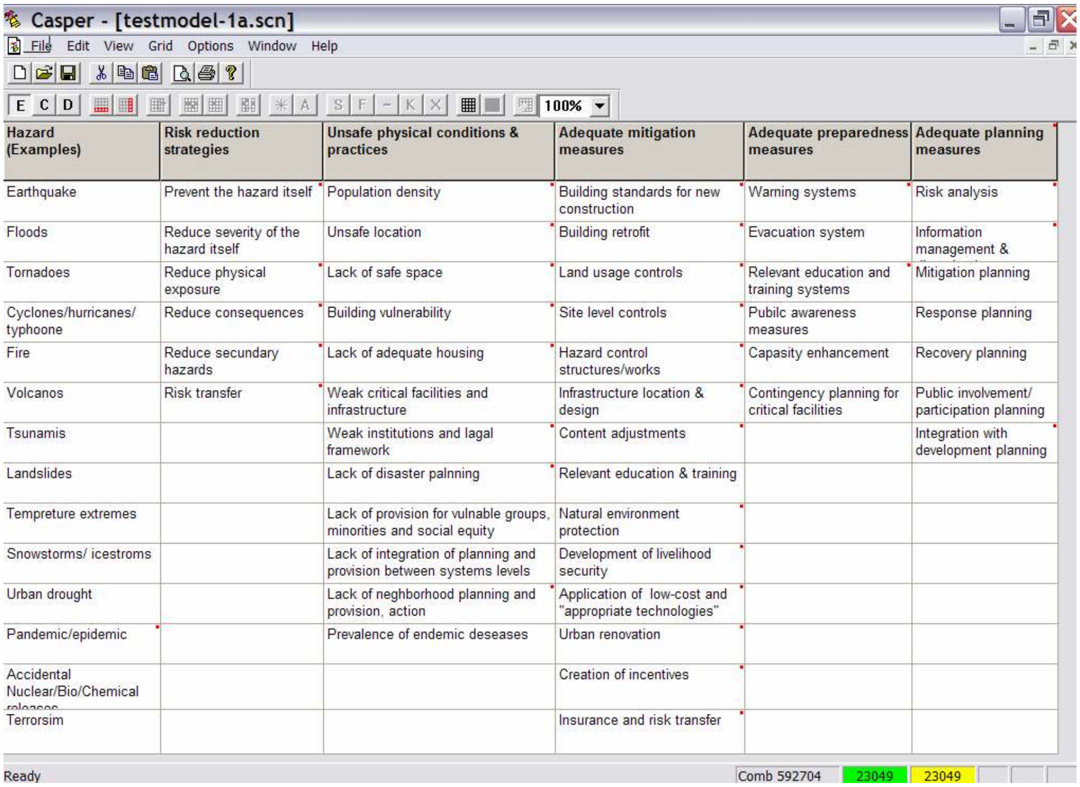
It is seldom practical to work with eleven parameters in a single model, as it could contain hundreds of millions of possible configurations. Normally, we would create two models with these eleven parameters, each containing one or two *common* parameters (e.g. "Types of hazards" and "Principle risk reduction strategies"). However, since we had only two days for our work, the group chose six of the parameters in order to develop a single "proof-of-principle" prototype.

Figure 1 shows the six selected parameters and their ranges of conditions. Figure 2 shows the Cross-consistency matrix and its assessments. For this model, we utilized three "keys" for the cross-consistency assessment:

"—" = These two conditions can/should co-exist.

"X" = These two conditions cannot/should not, co-exist.

"K" = These two conditions can co-exist, but are highly unlikely or uninteresting.



Hazard (Examples)	Risk reduction strategies	Unsafe physical conditions & practices	Adequate mitigation measures	Adequate preparedness measures	Adequate planning measures
Earthquake	Prevent the hazard itself	Population density	Building standards for new construction	Warning systems	Risk analysis
Floods	Reduce severity of the hazard itself	Unsafe location	Building retrofit	Evacuation system	Information management &
Tornadoes	Reduce physical exposure	Lack of safe space	Land usage controls	Relevant education and training systems	Mitigation planning
Cyclones/hurricanes/ typhoone	Reduce consequences	Building vulnerability	Site level controls	Pubilc awareness measures	Response planning
Fire	Reduce secundary hazards	Lack of adequate housing	Hazard control structures/works	Capasity enhancement	Recovery planning
Volcanos	Risk transfer	Weak critical facilities and infrastructure	Infrastructure location & design	Contingency planning for critical facilities	Public involvement/ participation planning
Tsunamis		Weak institutions and lagal framework	Content adjustments		Integration with development planning
Landslides		Lack of disaster palnning	Relevant education & training		
Tempreture extremes		Lack of provision for vulnable groups, minorities and social equity	Natural environment protection		
Snowstorms/ icestroms		Lack of integration of planning and provision between systems levels	Development of livelihood security		
Urban drought		Lack of neghborhood planning and provision, action	Application of low-cost and "appropriate technologies"		
Pandemic/epidemic		Prevalence of endemic deseases	Urban renovation		
Accidental Nuclear/Bio/Chemical			Creation of incentives		
Terrorsim			Insurance and risk transfer		

Figure 1. Prototype multi-hazard disaster reduction field.

We were not able to complete the cross-consistency assessment during the two-day workshop. Two EDM participants (Britton and Fernandez) finished the assessments, "back-office" so to speak, without facilitation. For this reason, the model should be regarded as a prototype for proof-of-principle. Its content will require a thorough revision and expansion before it can be considered a practical working model.

The model is examined by selecting alternative sets of *drivers*, in order to see how parameter values relate to each other. For instance, one of the most natural drivers would be the "hazard types" themselves. If we select "Earthquake", we get the morphology shown in Figure 3.

Multiple drivers can be selected in order to investigate more detailed conditions. For instance, a "Hazard type", a "Risk reduction strategy" and a particular "Unsafe physical condition & practice" can be examined in order to compare disaster reduction strategies for different hazards. (Figures 4, 5 and 6).

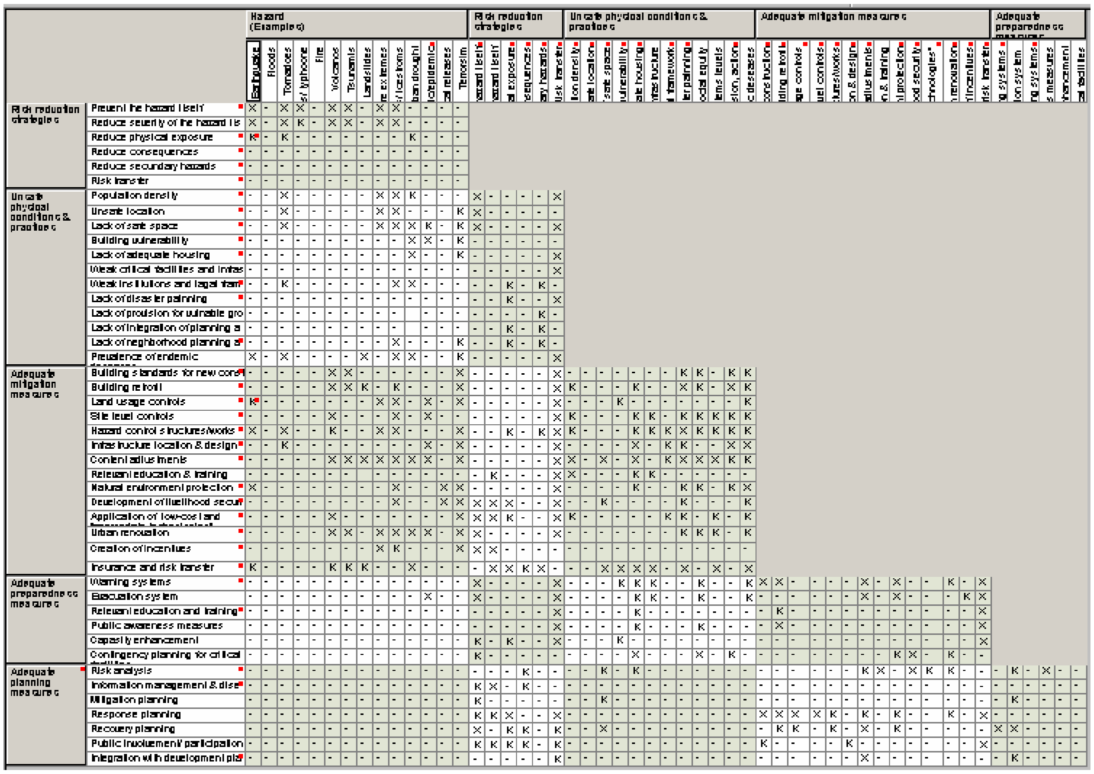
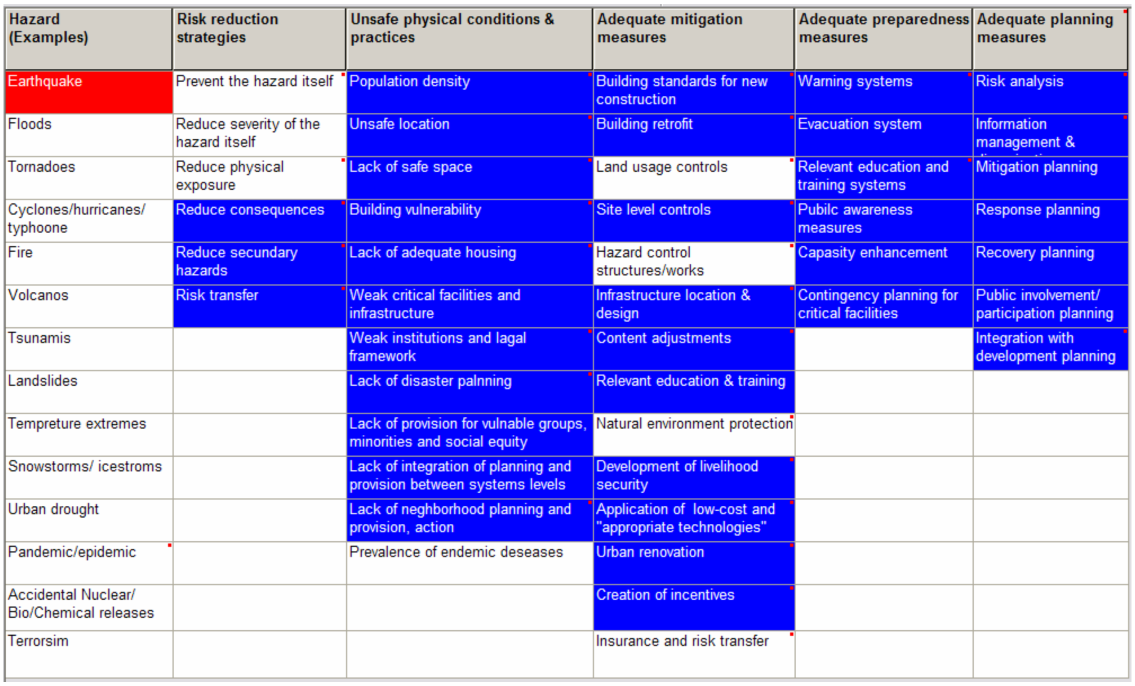
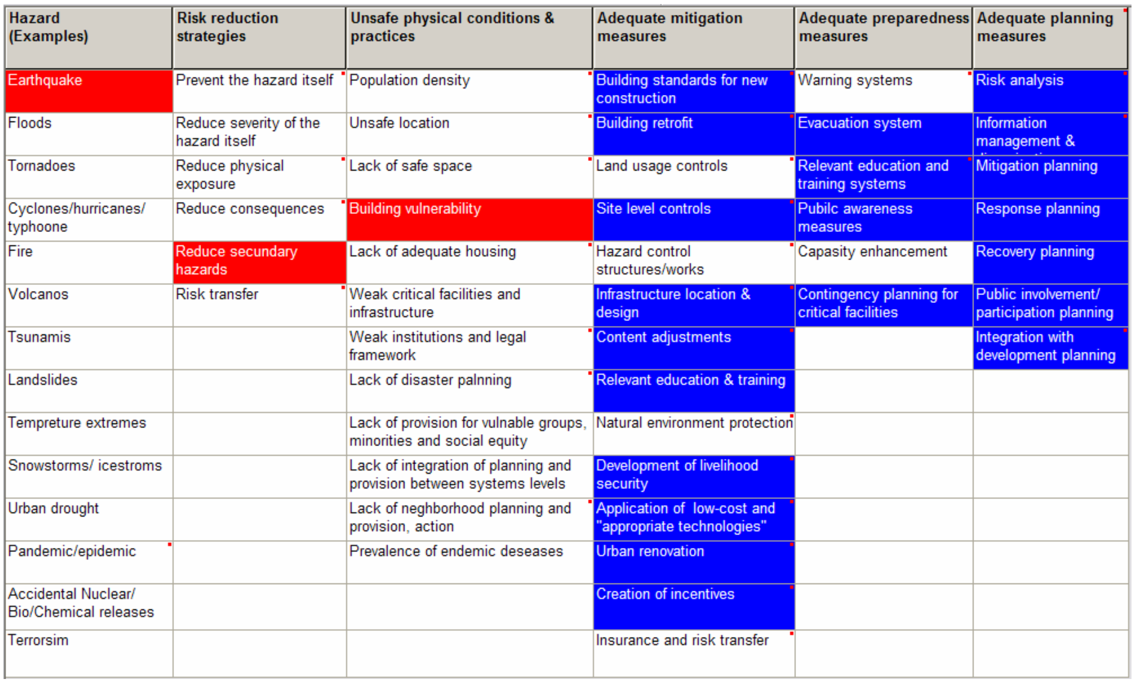


Figure 2. Cross-consistency matrix with assessments.



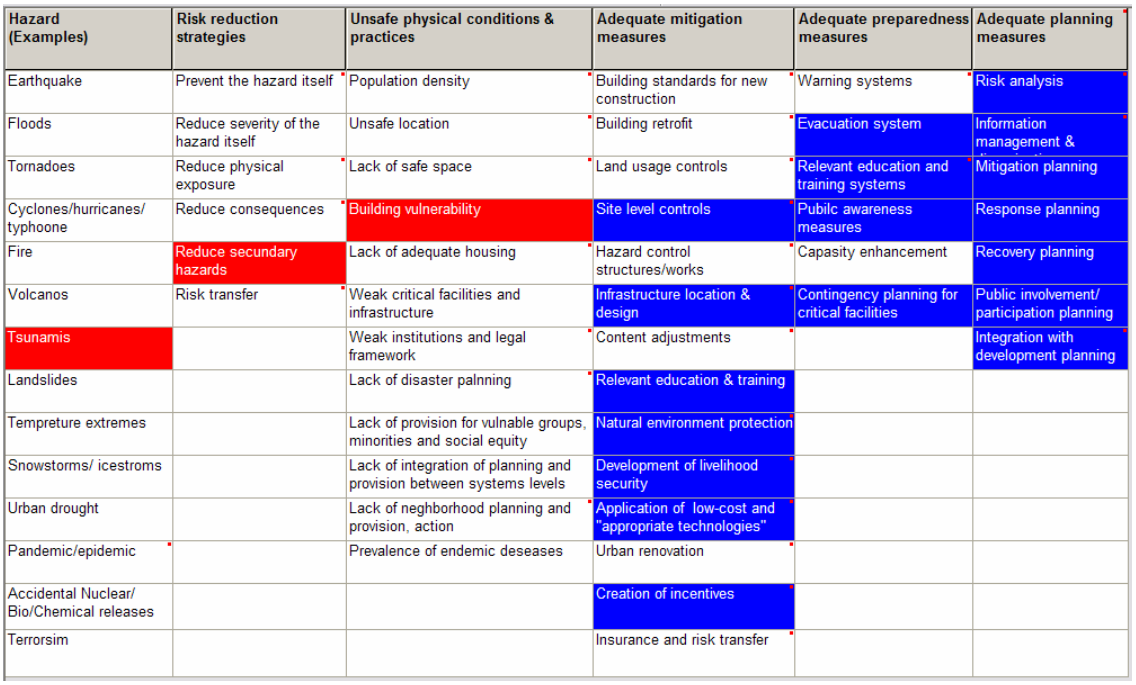
Hazard (Examples)	Risk reduction strategies	Unsafe physical conditions & practices	Adequate mitigation measures	Adequate preparedness measures	Adequate planning measures
Earthquake	Prevent the hazard itself	Population density	Building standards for new construction	Warning systems	Risk analysis
Floods	Reduce severity of the hazard itself	Unsafe location	Building retrofit	Evacuation system	Information management &
Tornadoes	Reduce physical exposure	Lack of safe space	Land usage controls	Relevant education and training systems	Mitigation planning
Cyclones/hurricanes/ typhoone	Reduce consequences	Building vulnerability	Site level controls	Pubilc awareness measures	Response planning
Fire	Reduce secundary hazards	Lack of adequate housing	Hazard control structures/works	Capasity enhancement	Recovery planning
Volcanos	Risk transfer	Weak critical facilities and infrastructure	Infrastructure location & design	Contingency planning for critical facilities	Public involvement/ participation planning
Tsunamis		Weak institutions and lagal framework	Content adjustments		Integration with development planning
Landslides		Lack of disaster palnning	Relevant education & training		
Tempreture extremes		Lack of provision for vulnable groups, minorities and social equity	Natural environment protection		
Snowstorms/ icestroms		Lack of integration of planning and provision between systems levels	Development of livelihood security		
Urban drought		Lack of neghborhood planning and provision, action	Application of low-cost and "appropriate technologies"		
Pandemic/epidemic		Prevalence of endemic deseases	Urban renovation		
Accidental Nuclear/ Bio/Chemical releases			Creation of incentives		
Terrorsim			Insurance and risk transfer		

Figure 3. Earthquake morphology.



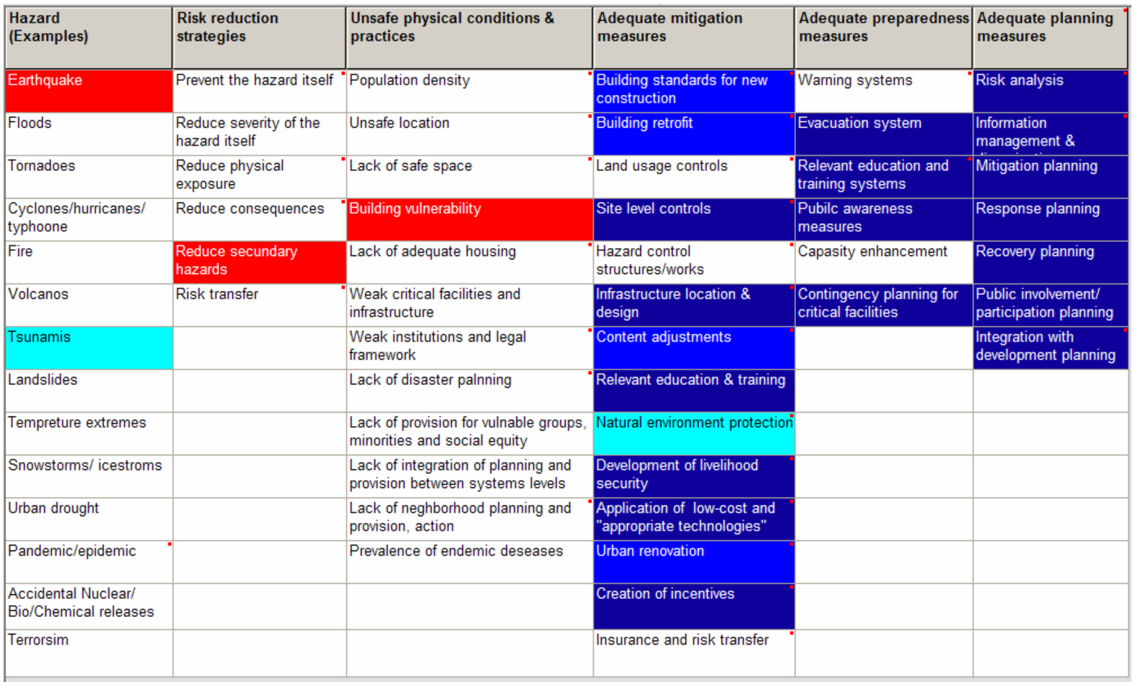
Hazard (Examples)	Risk reduction strategies	Unsafe physical conditions & practices	Adequate mitigation measures	Adequate preparedness measures	Adequate planning measures
Earthquake	Prevent the hazard itself	Population density	Building standards for new construction	Warning systems	Risk analysis
Floods	Reduce severity of the hazard itself	Unsafe location	Building retrofit	Evacuation system	Information management &
Tornadoes	Reduce physical exposure	Lack of safe space	Land usage controls	Relevant education and training systems	Mitigation planning
Cyclones/hurricanes/ typhoone	Reduce consequences	Building vulnerability	Site level controls	Pubilc awareness measures	Response planning
Fire	Reduce secundary hazards	Lack of adequate housing	Hazard control structures/works	Capasity enhancement	Recovery planning
Volcanos	Risk transfer	Weak critical facilities and infrastructure	Infrastructure location & design	Contingency planning for critical facilities	Public involvement/ participation planning
Tsunamis		Weak institutions and legal framework	Content adjustments		Integration with development planning
Landslides		Lack of disaster palnning	Relevant education & training		
Tempreture extremes		Lack of provision for vulnable groups, minorities and social equity	Natural environment protection		
Snowstorms/ icestroms		Lack of integration of planning and provision between systems levels	Development of livelihood security		
Urban drought		Lack of neghborhood planning and provision, action	Application of low-cost and "appropriate technologies"		
Pandemic/epidemic		Prevalence of endemic deseases	Urban renovation		
Accidental Nuclear/ Bio/Chemical releases			Creation of incentives		
Terrorsim			Insurance and risk transfer		

Figure 4. Multiple driver Earthquake morphology.



Hazard (Examples)	Risk reduction strategies	Unsafe physical conditions & practices	Adequate mitigation measures	Adequate preparedness measures	Adequate planning measures
Earthquake	Prevent the hazard itself	Population density	Building standards for new construction	Warning systems	Risk analysis
Floods	Reduce severity of the hazard itself	Unsafe location	Building retrofit	Evacuation system	Information management &
Tornadoes	Reduce physical exposure	Lack of safe space	Land usage controls	Relevant education and training systems	Mitigation planning
Cyclones/hurricanes/ typhoone	Reduce consequences	Building vulnerability	Site level controls	Pubilc awareness measures	Response planning
Fire	Reduce secundary hazards	Lack of adequate housing	Hazard control structures/works	Capasity enhancement	Recovery planning
Volcanos	Risk transfer	Weak critical facilities and infrastructure	Infrastructure location & design	Contingency planning for critical facilities	Public involvement/ participation planning
Tsunamis		Weak institutions and legal framework	Content adjustments		Integration with development planning
Landslides		Lack of disaster palnning	Relevant education & training		
Tempreture extremes		Lack of provision for vulnable groups, minorities and social equity	Natural environment protection		
Snowstorms/ icestroms		Lack of integration of planning and provision between systems levels	Development of livelihood security		
Urban drought		Lack of neghborhood planning and provision, action	Application of low-cost and "appropriate technologies"		
Pandemic/epidemic		Prevalence of endemic deseases	Urban renovation		
Accidental Nuclear/ Bio/Chemical releases			Creation of incentives		
Terrorsim			Insurance and risk transfer		

Figure 5. Multiple driver Tsunami morphology.



Hazard (Examples)	Risk reduction strategies	Unsafe physical conditions & practices	Adequate mitigation measures	Adequate preparedness measures	Adequate planning measures
Earthquake	Prevent the hazard itself	Population density	Building standards for new construction	Warning systems	Risk analysis
Floods	Reduce severity of the hazard itself	Unsafe location	Building retrofit	Evacuation system	Information management &
Tornadoes	Reduce physical exposure	Lack of safe space	Land usage controls	Relevant education and training systems	Mitigation planning
Cyclones/hurricanes/ typhoone	Reduce consequences	Building vulnerability	Site level controls	Pubilc awareness measures	Response planning
Fire	Reduce secundary hazards	Lack of adequate housing	Hazard control structures/works	Capasity enhancement	Recovery planning
Volcanos	Risk transfer	Weak critical facilities and infrastructure	Infrastructure location & design	Contingency planning for critical facilities	Public involvement/ participation planning
Tsunamis		Weak institutions and legal framework	Content adjustments		Integration with development planning
Landslides		Lack of disaster palnning	Relevant education & training		
Tempreture extremes		Lack of provision for vulnable groups, minorities and social equity	Natural environment protection		
Snowstorms/ icestroms		Lack of integration of planning and provision between systems levels	Development of livelihood security		
Urban drought		Lack of neghborhood planning and provision, action	Application of low-cost and "appropriate technologies"		
Pandemic/epidemic		Prevalence of endemic deseases	Urban renovation		
Accidental Nuclear/ Bio/Chemical releases			Creation of incentives		
Terrorsim			Insurance and risk transfer		

Figure 6. Comparison between Earthquake and Tsunami morphologies. Dark blue represents common disaster reduction measures. Light blue represents reduction measures for Tsunamis only, and middle blue represents reduction measure for Earthquakes only.

CONCLUSIONS

Morphological analysis, extended by the technique of "cross-consistency assessment", is based on the fundamental scientific method of analysis – synthesis cycles. For this reason, it can be trusted as a useful, conceptual modeling method for investigating non-quantified problem complexes, which cannot be treated by formal mathematical methods, causal modeling and simulation.

The prototype multi-hazard disaster reduction model presented here is neither complete nor fully accurate; its content needs to be expanded and refined. The model does, however, represent a proof-of-principle, since it makes it possible to compare adequate disaster reduction measures for different hazards and different principle risk reduction strategies.

It is also important to emphasize the utility of the *modeling process* itself. The morphology workshop was a success, not the least for permitting cross-fertilization of ideas and knowledge between hard and soft sciences, and between theory and practice. Using this modeling method, the specialists developed shared concepts and a "common working interface", shared definitions of parameters and conditions, and shared state-of-the-art knowledge from different fields. In the process, they identified areas where further research is needed. The specialists concluded that the method has considerable value for DRM, and that the main advantage lies in enabling practitioners and researchers to better structure their thinking in DRM and to deal with disaster risks more holistically (Fernandez, et. al., 2006).

Further work will aim at expanding and refining the model, and developing products such as guidelines and diagnostic tools. As suggested during the workshop, the team might produce a tool for city and town managers, as they seek to manage their own risks in urban centres of megacities.

ACKNOWLEDGMENTS

Thanks to the workshop participants:

- Dr. Fouad Bendimerad (Hazard management, USA), Chairman, Earthquake and Megacities Initiative (EMI)
- Dr. Niel Britton (Integrated risk management/disaster management, Japan) Team Leader, International Disaster Reduction Strategies Research Team at the Earthquake Disaster Mitigation Research Center

- Dr Raymond Burby (Land-use management/hazard management, USA), Professor of City & Regional Planning, University of North Carolina at Chapel Hill
- Ms Kerstin Castenfors (Crisis management., Sweden), Deputy Director of Research, Dept. of International Security Studies (Division of Defence Analysis), Swedish National Defence Research Agency (FOI)
- Dr. Ian Davis (Development and sustainability, United Kingdom), Visiting Professor in Cranfield University, and Visiting Fellow in York and Oxford Brookes Universities
- Dr. Tony Fernandez, (Environmental planning and sustainability) Policy Implementation Researcher, EDM
- Ms Shirley Mattingly (Disaster management/public administration practice and public policy, USA), Project Director, Cross-Cutting Capacity Development Program, EMI, and former Head of Disaster Management for the City of Los Angeles.

The author facilitated the morphological modeling process.

REFERENCES

Britton, Neil (2005). Developing a framework for identifying sound practices in megacities. 1st International Conference on Urban Disaster Research, 18-20 January 2005, Kobe, Japan (available at: http://www.edm.bosai.go.jp/team4/3cd/index).

Coyle, R. G., Crawshay, R. and Sutton, L. (1994). "Futures Assessments by Field Anomaly Relaxation". *Futures* 26(1), 25-43.

Eriksson, T. & Ritchey, T. (2002). Scenario Development and Force Requirements using Morphological Analysis. Presented at the Winchester International OR Conference, Winchester, March 2002.

Fernandez, A., Britton, N. & Ritchey, T. (2006) Application of a Prototype Morphological Model for Earthquake Disaster Risk Management. Presented at the 2nd Asia Conference on Earthquake Engineering 2006, March 10-11, 2006, Manila

Greenstein J. and Wilson A. (1974). "Remembering Zwicky". *Engineering and Science 37:15*-19.

Mattingly, Shirley (2002) Policy, legal and institutional arrangements. Proceedings. Regional Workshop on Best Practices in Disaster Mitigation, Sept. 24-26, 2002, Bali, pp. 19-36.

Rhyne, R. (1995). "Field Anomaly Relaxation – The Arts of Usage", *Futures* 27 (6), 657-674.

Ritchey, T. (1991). (Reprint 1996). "Analysis and Synthesis - On Scientific Method based on a Study by Bernhard Riemann". *Systems Research 8*(4), 21-41. (Reprint available at: www.swemorph.com/method.)

Ritchey, T. (1997). "Scenario Development and Risk Management using Morphological Field Analysis". In *Proceedings of the 5th European Conference on Information Systems.* (Cork: Cork Publishing Company) Vol. 3:1053-1059.

Ritchey, T. (2003). "Nuclear Facilities and Sabotage: Using Morphological Analysis as a Scenario and Strategy Development Laboratory". In *Proceedings of the 45th Annual Meeting of the Institute of Nuclear Materials Management* (Phoenix, AZ, July 5-9). (Download available at: www.swemorph.com/pdf/inmm-r2.pdf.)

Stenström, M. and Ritchey, T. (2002). "Using Morphological Analysis to Evaluate Preparedness for Accidents Involving Hazardous Materials". In *Proceedings of the 4th International Conference on Local Authorities Confronting Disasters and Emergencies* (Shanghai, November 20-24). (Download available at: www.swemorph.com.)

Zwicky, F. (1969). *Discovery, Invention, Research - Through the Morphological Approach.* The Macmillan Company, Toronto.

Zwicky, F. and Wilson A. (editors). (1967). *New Methods of Thought and Procedure: Contributions to the Symposium on Methodologies*. Springer, Berlin.