Space Weather and Water infrastructure

Do Space Storms pose a risk to the Australian Water Sector (and what might be done about it)?

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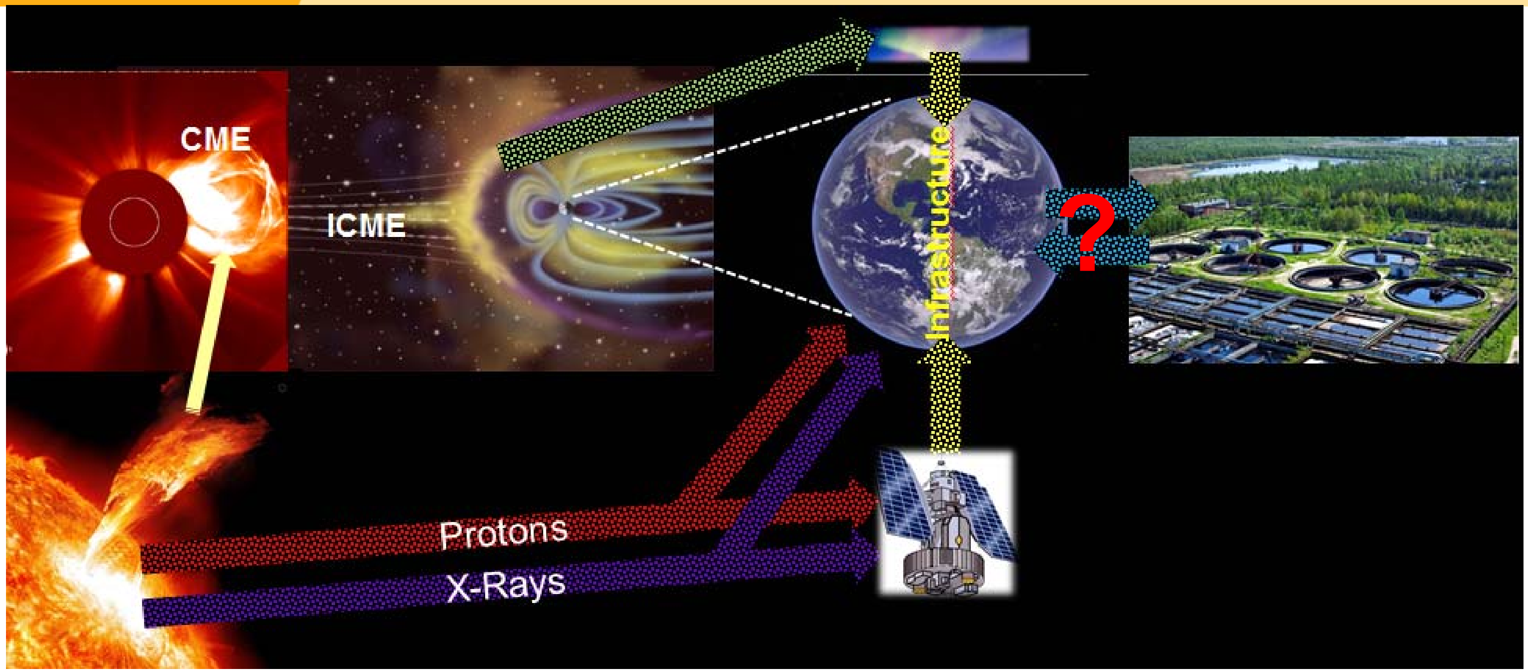
Never Stand Still



Perspective/interest

Space Weather =>? Water sector

1. Sydney Water Systems analysis FITZGERALD, S. K., OWENS, C., ANGLES, M., HOCKADAY, D., BLACKMORE, M. & FERGUSON, M. 2017. Reframing risk: a risk pathway method for identifying improvement through control and threat analysis. *Water Science and Technology: Water Supply*.

2. Concerns of journalist friend

3. Concern about no water literature found in topic search

4. Curiosity

Perspective/interest

Address following questions – with a review of water sector impacts in mind

1. **Is there an "existential risk" from extreme solar storms of concern to the water sector?** *How do Average Recurrence Intervals (ARIs) for other extreme events compare?*

2. **How important is interdependency?** *How might the water sector be vulnerable to solar storms via interdependency paths?*

3. **Are formal risk assessment and management frameworks applicable & sufficient?** *How might interdependency be analysed? (Bayes Nets?)*

4. **Policy implications?** *Water a model for other sectors?*

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How do solar storms and other major <u>physical</u> existential risks compare ?

Event	ARI (y)	Size/Details	Notes	Refs.
≈Carrington event	*ca* 100	-*Dst* = 600-1800 nT/min ≈10^{25} J?	Reasonably understood, good magnitude estimates	NEUHAEUSER, R. & HAMBARYAN, V. 2014. A solar super-flare as cause for the 14C variation in AD 774/5? Astronomische Nachrichten, 335, 949-963. SHIBATA, K., ISOBE, H., HILLIER, A., CHOUDHURI, A. R., MAEHARA, H., ISHII, T. T., SHIBAYAMA, T., NOTSU, S., NOTSU, Y. & NAGAO, T. 2013. Can superflares occur on our Sun? Publications of the Astronomical Society of Japan, 65, 49. LOVE, J. J. 2012. Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms. Geophysical Research Letters, 39, doi:10.1029/2012GL051431. FUKUTANI, Y., SUPPASRI, A. & IMAMURA, F. 2015. Stochastic analysis and uncertainty assessment of tsunami wave height using a random source parameter model that targets a Tohoku-type earthquake fault. Stochastic Environmental Research and Risk Assessment, 29, 1763-1779. HENSON, B. 2017. Harvey in Houston: Most Extreme Rains Ever For a Major U.S. City August 29, 2017, 3:02 PM EDT https://www.wunderground.com/cat6/harvey-houston-most-extreme-rains-ever-major-us-city. Weather Underground [Online]. EMANUEL, K. 2008. The Hurricane—climate connection. Bulletin of the American Meteorological Society, 89, ES10-ES20. BRYANT, E. A. & NOTT, J. 2001. Geological Indicators of Large Tsunami in Australia. Natural Hazards, 24, 231-249. MASON, B. G., PYLE, D. M. & OPPENHEIMER, C. 2004. The size and frequency of the largest explosive eruptions on Earth. Bulletin of Volcanology, 66, 735-748.
774/775 CE	≈1250-3000?	-*Dst* = 2500? 4-6 X Carrington ≈10^{26} J?	Not understood - duration? Indicators? beam angle??	
VEI=7 Eruption	≈500	1815 Tambora *ca* 10^{20} J	0.5 °C drop,100 km^3 ejecta/ Eyjafjallajökull 2010 VEI=4	
Extreme 24h rainfall	*500 - >1000*	*10^{21} J heat transfer per Hurricane*	*Houston 2017, local effect*	
Tohuku earthquake (Fukushima)	*1700*	*Tectonic area. Mag 9.1 (≈10^{18} J)*	*Large, unexpected, impact semi-local - compare 1960 Chile 9.5 to max of 10*	
Paleo-Tsunami	*2000*	*East Australia coast >desalination plant*	*Limited data on causes, local effect*	
Dams fail	*>10,000*	*Tolerable ALARP*	*Local earthquake trigger?*	
VEI=8 eruption	≈100,000	5 x 10^{20} J	Most recent Taupo and Toba at 26k & 76k BP	
Large Asteroids	> 3,000,000	Eruption energy crossover 10^{21} J	Energy from asteroid > from volcanic eruptions	

(*Red events = local*, violet events are global
nuclear apocalypse & cosmogenic horsemen not considered)

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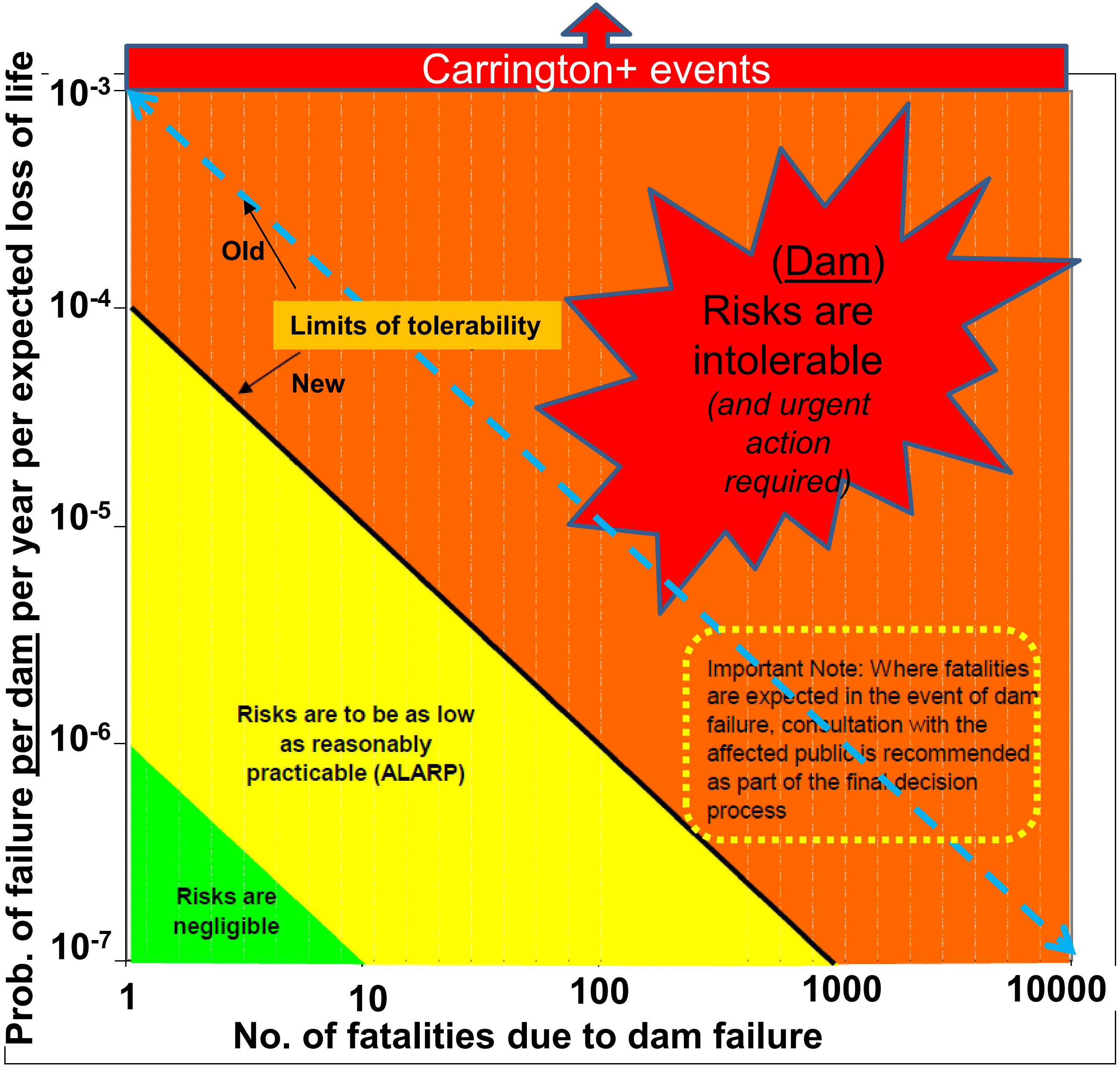
Water sector historical response to low probability, high consequence risks?

Warragamba auxiliary spillway for 750 y ARI flood cost AUD100,000,000 (2002)

(http://www.waternsw.com.au/supply/Greater-Sydney/safety/warragamba-dam-auxiliary-spillway)

1. Existential risks – versus tolerable water risk

Water sector risk benchmark probabilities compare to those for solar storms?



Proposed DSC Societal Risk requirements for new dams and major augmentations

Value of human life in ≈ $1-10 million

Refs. BOWLES, D. S. 2001. Evaluation and use of risk estimates in dam safety decision making - http://www.academia.edu/download/34108419/asdsopap.pdf. Risk-Based Decision making in Water Resources IX.

NSW GOVERNMENT DAM SAFETY COMMITTEE 2006. Risk Management Policy Framework For Dam Safety. 18pp.

Conclusions

- **Extreme solar storms (ARI>100 y) are much more likely than other large existential risks.** *(but small, ARI<50 y, solar storms seem satisfactorily managed)*

- **Probability of "Carrington" and "Carrington+" events >> water sector "Tolerable Risk" benchmarks.** *Tolerable Risk v. ARI comparison is an established management prioritization technique. But what value to assign to solar storms?*

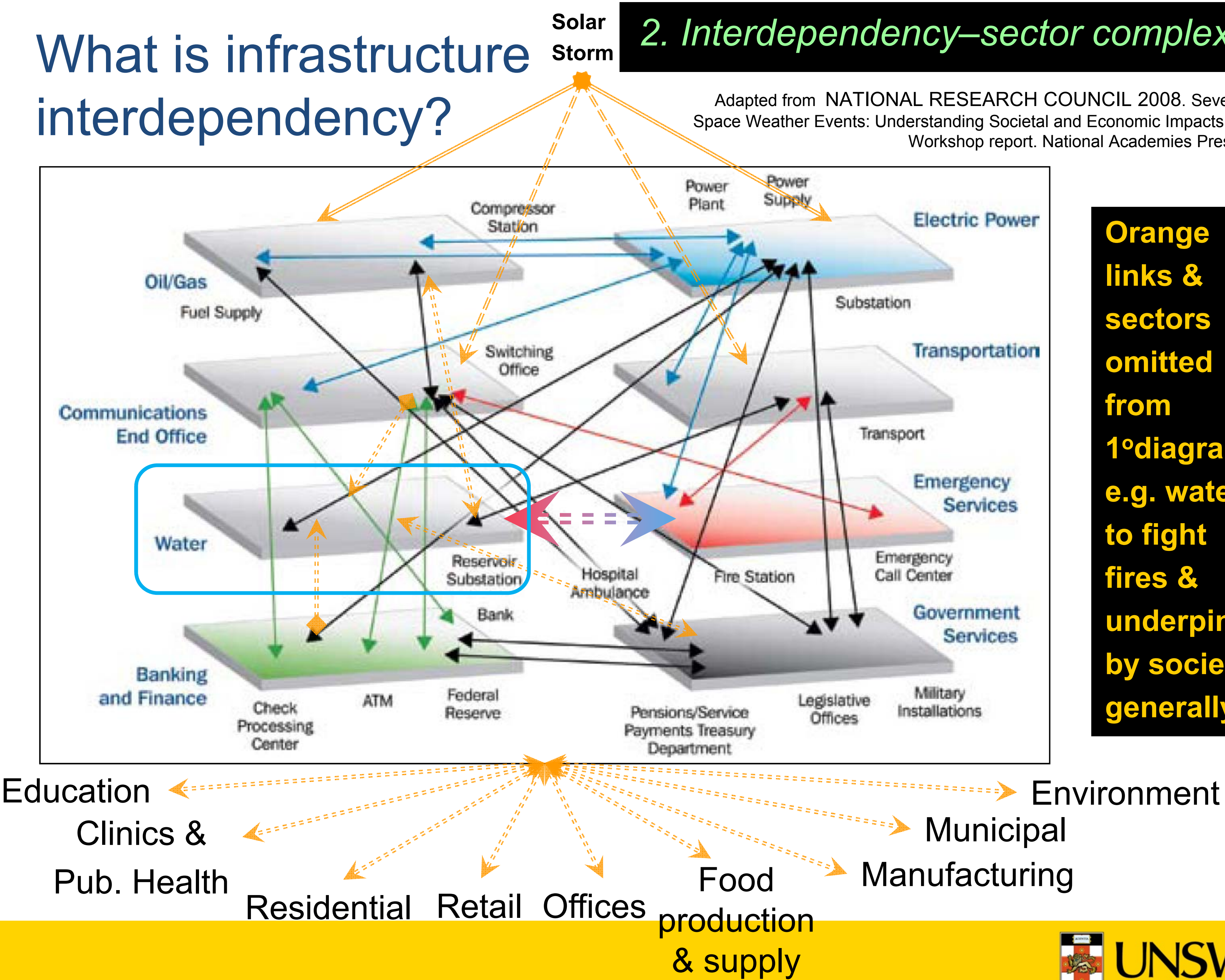
While direct physical impacts on water sector are probably limited (metal pipelines, telemetry) what about multi-sector **interdependency***?*

Understanding/considering Interdependency ?>>>

What is infrastructure interdependency?

2. Interdependency–sector complexity

Adapted from NATIONAL RESEARCH COUNCIL 2008. Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop report. National Academies Press.



Orange links & sectors omitted from 1ºdiagram e.g. water to fight fires & underpin by society generally

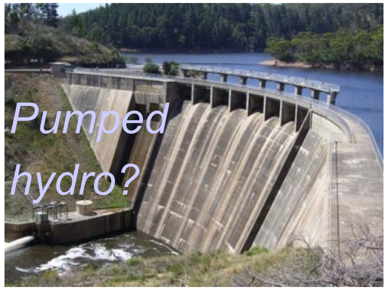
Water sector vulnerability to power loss? Tolerable duration?

2. Interdependency – specific vulnerabilities

Clean H_2O 'value'? *ca* USD 250 <u>person^{-1} y^{-1}</u> (2003)
<u>public health alone</u> – social rate of return – 23:1

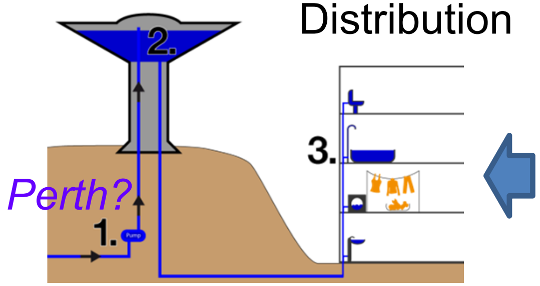
CUTLER, D. & MILLER, G. 2005. The role of public health improvements in health advances: The twentieth-century United States. Demography, 42, 1-22.

Source/Hydro/Flood control



Drinking H_2O Treatment

Groundwater extraction/ Distribution



Urban hi-rise?

Sewage treatment

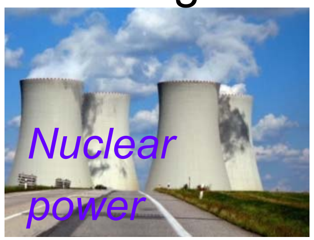
UF/RO (desalination/ wastewater)

Farming/Irrigation

Food/Beverage

Industrial washing

Cooling/AC

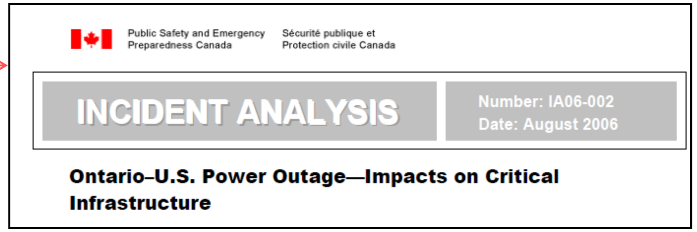


Cooking H_2O options?

(20 L/p/d minimum for refugee camps)

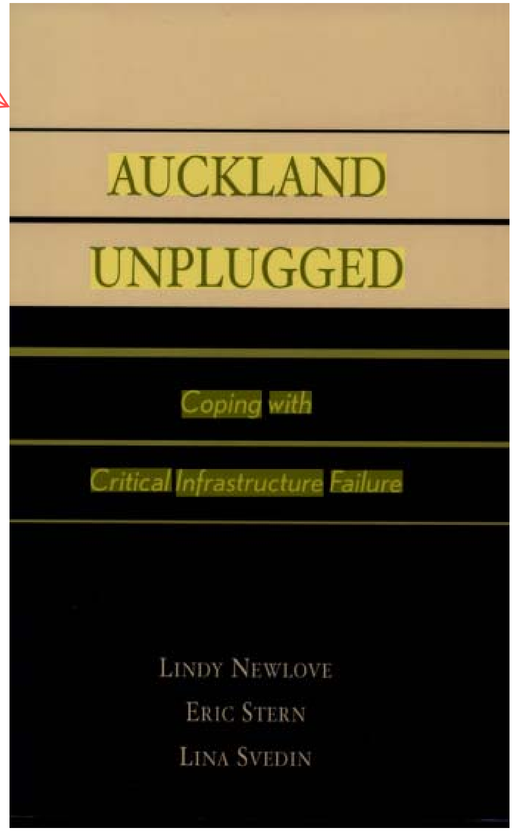
Are concerns valid? What can other event experiences tell us?

2003 Canada/US power outage (blackstart/scale)
1998 Auckland power failure (impact of long duration)


Public Safety and Emergency Preparedness Canada / Sécurité publique et Protection civile Canada

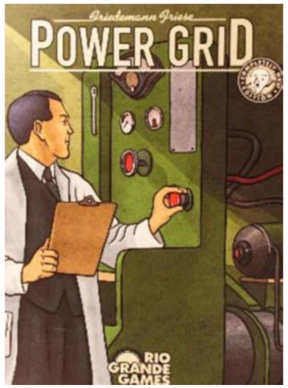
INCIDENT ANALYSIS — Number: IA06-002 — Date: August 2006

Ontario–U.S. Power Outage—Impacts on Critical Infrastructure



Water sector effects include loss of:

- Groundwater extraction and pump transfers
- Water pressure for high rise
- Fire service hydrants



Other issues:

- A two to four week supply of chemicals
- Reduction in reservoir reserves
- Sewage flushing
- Raw sewage discharges/overflows
- Local water shortages
- Backup failures
- Boil water alerts
- *Replacing damaged equipment*
- *By-pass overflow and compensation*
- *Beach closures*
- *Pumping facilities*
- Blackstart delay v. available backup diesel generators & fuel supply limits
- A possible chemical release into the sewers from a commercial manufacturer
- *Dependency on utilities including gas, water, electricity, telecommunications and chemical/equipment suppliers*

Auckland rescued by outside help, Canada/US 2003 by rapid cessation of cause, limited damage & grid structure

2. Interdependency lessons B. 'Management of Natural Experiments'

Is Extreme 'Environmental' Event Management up to scratch?

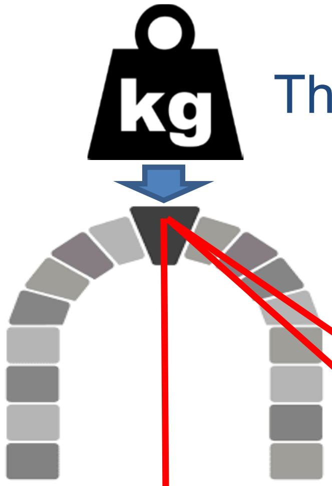
Crisis Years	Aware-ness	Event	Extent to which addressed	Status
1985-1987	1970s	Ozone Hole	reasonable	Timely response ?receding
1995-2000	1970s	Y2K	deadline driven	Timely /resolved
1800s+	1952	NOx,SO_2 pollution	Excellent > v. poor	Varied
e.g. 2005, 2012, 2017	Pre-historic	US Hurricanes > large floods	Ok unless 100 y ARI exceeded	Partially **ARI** managed
2011	1950s	Fukushima	Remediation still incomplete	Partially **ARI** managed
1980s-?	1960s	Antibiotic resistance	Reasonable but still incomplete	Solutions exist but unresolved
1992-??	1958	Climate change	v. slow / not	Unresolved
2017+?	2005	Mosul Dam	Not addressed?	Unresolved
10,000 BCE-??	1800s	The 6th Extinction Holocene	v. slow /not	Unresolved

Less than satisfactory management reflects competition between environmental versus and human demands.= economics

Green=satisfactory, yellow = problematic, pink = unsatisfactory

2. Interdependency lessons C. complex ecosystem

Ecosystem experience from damaging, protecting & restoring

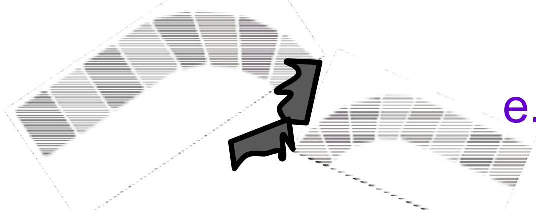


The 'Keystone' concept

"**Keystone species** *have disproportionately high importance in their community…*

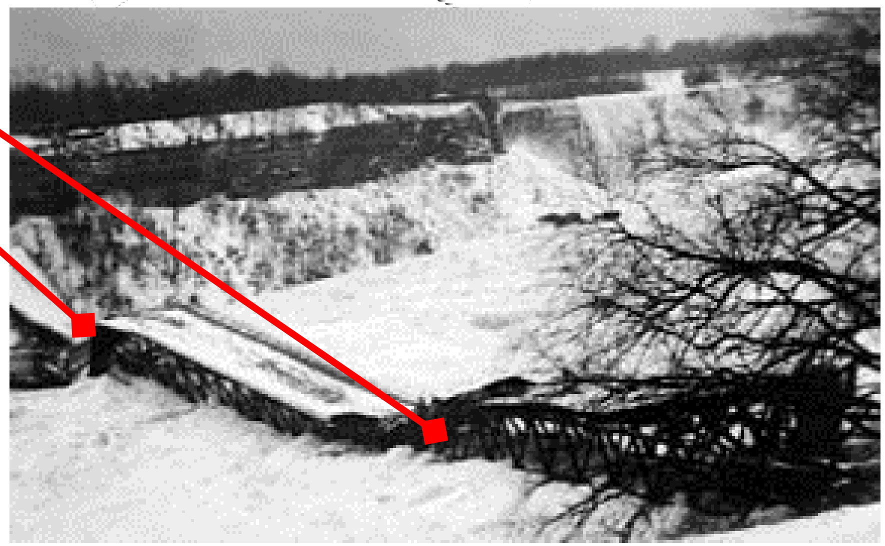
Keystone ecological structures *….(provide) resources shelter or 'goods and services' crucial for other species'*

…. **Keystone habitats** *(maintain) biodiversity"**



e.g. mangroves & elephants

Critical units fail, >most function lost, restoration hard



*MOUQUET, N., GRAVEL, D., MASSOL, F. & CALCAGNO, V. 2013. Extending the concept of keystone species to communities and ecosystems. Ecology Letters, 16, 1-8.

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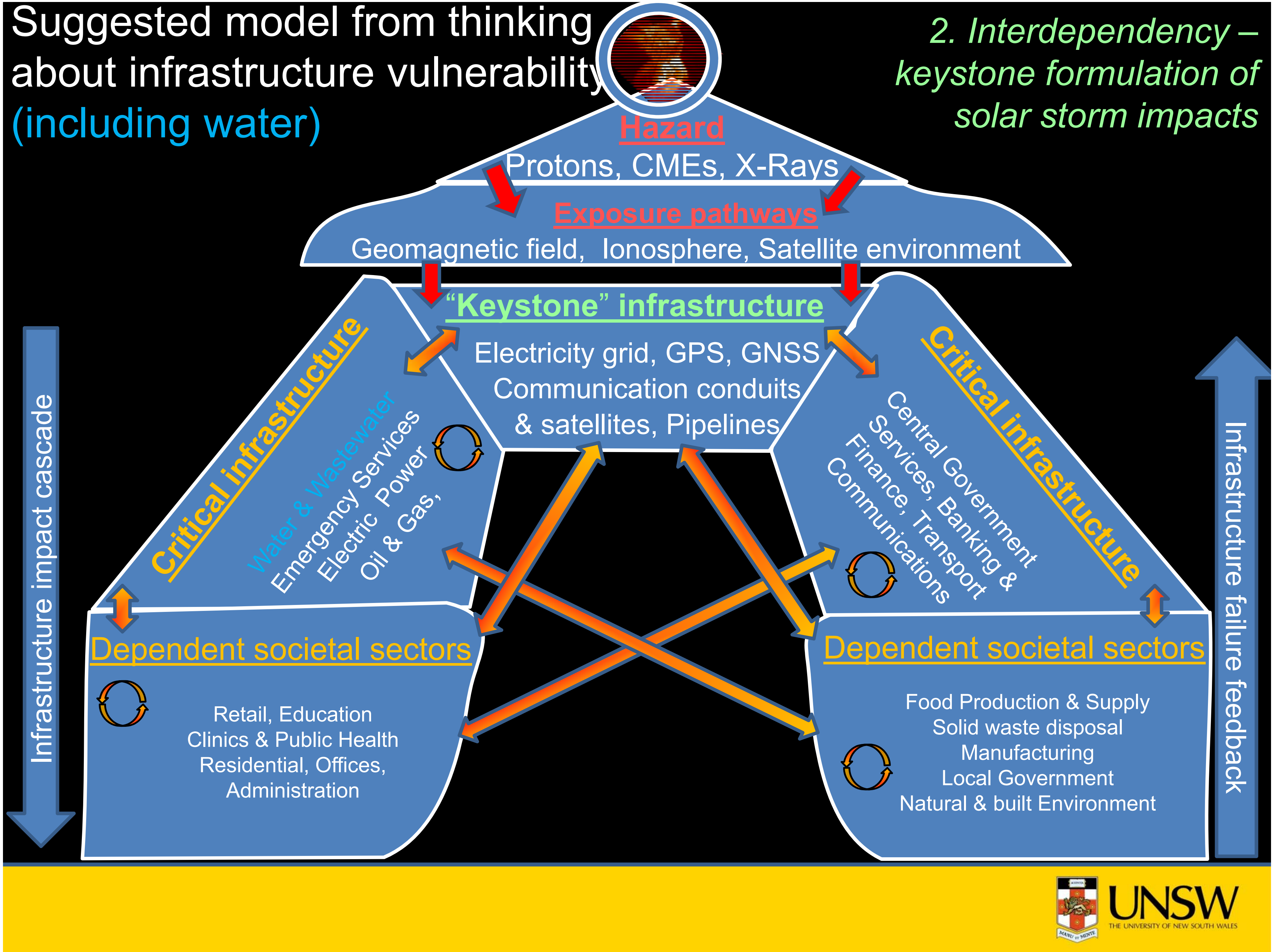
Suggested model from thinking about infrastructure vulnerability (including water)
2. Interdependency – keystone formulation of solar storm impacts
Hazard
Protons, CMEs, X-Rays
Exposure pathways
Geomagnetic field, Ionosphere, Satellite environment
"Keystone" infrastructure
Electricity grid, GPS, GNSS
Communication conduits
& satellites, Pipelines
Critical infrastructure
Water & Wastewater
Emergency Services
Electric Power
Oil & Gas,
Critical infrastructure
Central Government
Services, Banking &
Finance, Transport
Communications
Dependent societal sectors
Retail, Education
Clinics & Public Health
Residential, Offices,
Administration
Dependent societal sectors
Food Production & Supply
Solid waste disposal
Manufacturing
Local Government
Natural & built Environment
Infrastructure impact cascade
Infrastructure failure feedback
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Conclusions

- **Water is probably vulnerable to extreme solar storms via interdependency** (*& a critical (model?) sector in the modern built infrastructure system)*

- **Extreme event risk management generally is still immature**

- **Water is at risk from prolonged 'keystone' infrastructure failure** *(along with all other critical infrastructure whose interdependency must also be considered)*

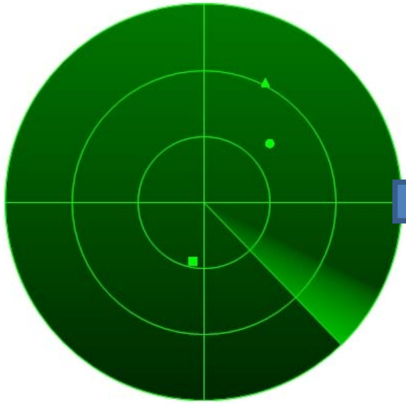
How to respond? - A. Implement Better Risk Management >>>How?

What management ideas, options & issues might be considered?

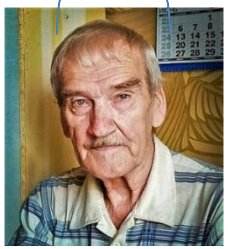
(HEMP methods probably inapplicable)

Storm source (Sun) & limited warning precludes much human intervention (unlike with HEMP accident/ error/ misunderstanding)

∴ Management must be **proactive** not reactive



e.g. 1962,1967,1979,1983,1995



Stanislav Petrov
1939-2017

*

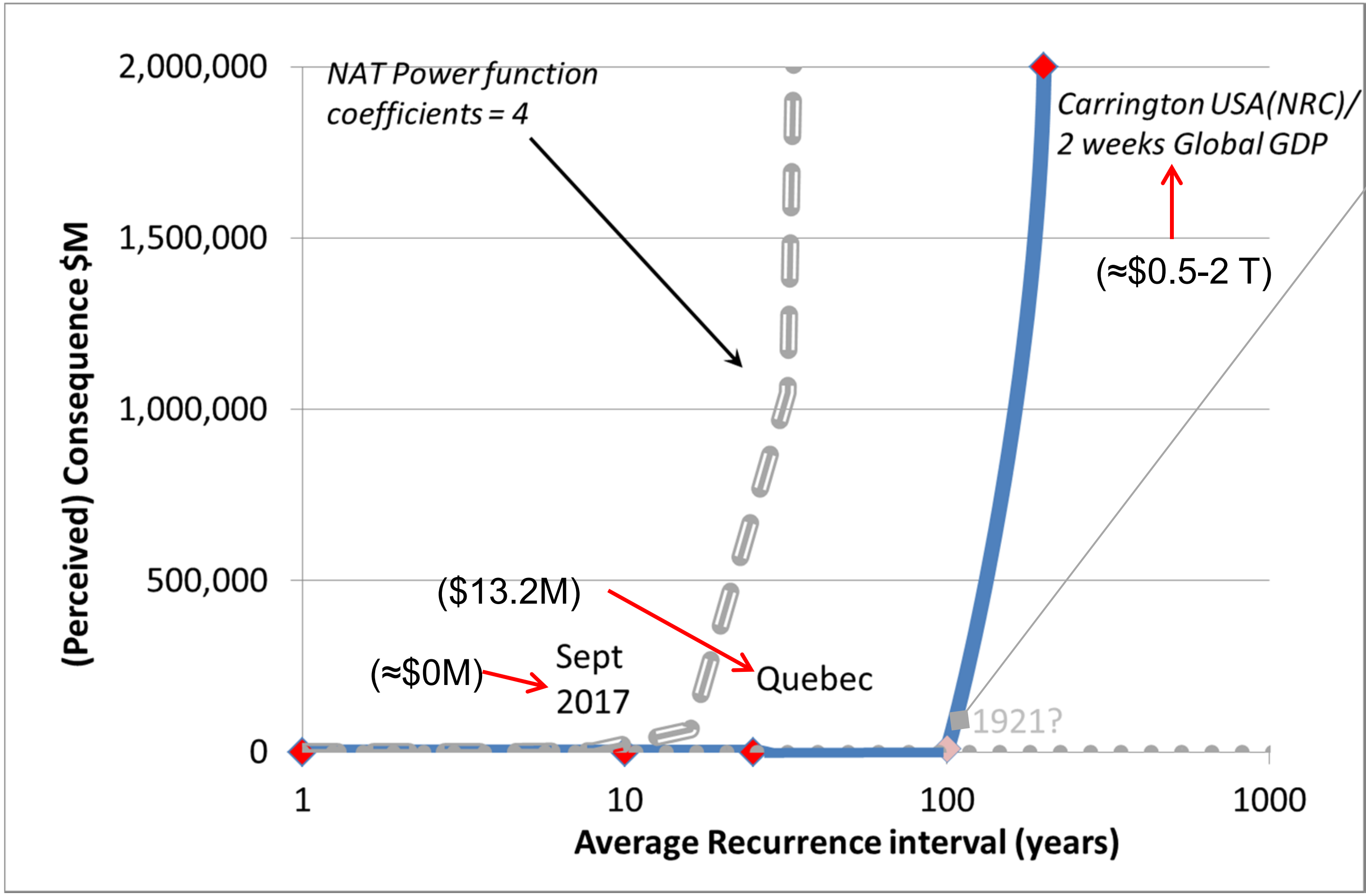
*

* Minuteman Missile National Historic Site – cf. https://en.wikipedia.org/wiki/Minuteman_Missile_National_Historic_Site

3. Risk Management - understanding extremes

“Normal Accident Theory”
power curves > help understand solar storm risk
e.g. ARIs & quantifiable tolerable risks!

(Versus experience based (reactive) “High Reliability Theory”)



Inflexion point due to?

Hypergeometric/ 4th power impact increase

X *Resilience & infrastructure tuned to small events*

X *Aurora current expansion*

X *Multiple storms*

X *Increasing Interdependency impact*

v. useful start but doesn’t yet provide TTD list

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3. Risk management - tools and toolkits

Q. What about operational management methods? What are available?

A. Various e.g. ISO 31010 & AS/NZS Risk Management Stds

Key operational risk management steps:

1. Risk Identification
2. Risk analysis
   a. Control effectiveness
   b. Consequences
   c. Likelihood
   d. Estimate level
3. Risk evaluation

(? And complex system interactions)

Water sector employs many risk tools

1. Brainstorming
2. Structured or semi-structured interviews
3. Delphi
4. **Check-lists**
5. Primary hazard analysis
6. Hazard and operability studies (HAZOP)
7. **Hazard Analysis and Critical ControlPoints (HACCP)**
8. **Environmental risk assessment**
9. Structure « What if? » (SWIFT)
10. Scenario analysis
11. Business impact analysis
12. Root cause analysis
13. Failure mode effect analysis
14. **Fault tree analysis**
15. **Event tree analysis**
16. **Cause and consequence analysis**
17. Cause-and-effect analysis
18. Layer protection analysis (LOPA)
19. Decision tree
20. Human reliability analysis
21. **Bow tie analysis**
22. Reliability centred maintenance
23. Sneak circuit analysis
24. Markov analysis
25. **Monte Carlo simulation**
26. **Bayesian statistics and Bayes Nets**
27. FN curves
28. Risk indices
29. ***Consequence/ likelihood matrix***
30. Cost/benefit analysis
31. Multi-criteria decision analysis (MCDA)

Easy for prelim. analysis but deeply flawed for quantification – see L. Cox or Fenton analyses

Research must collect high quality decision supporting input data acquisition

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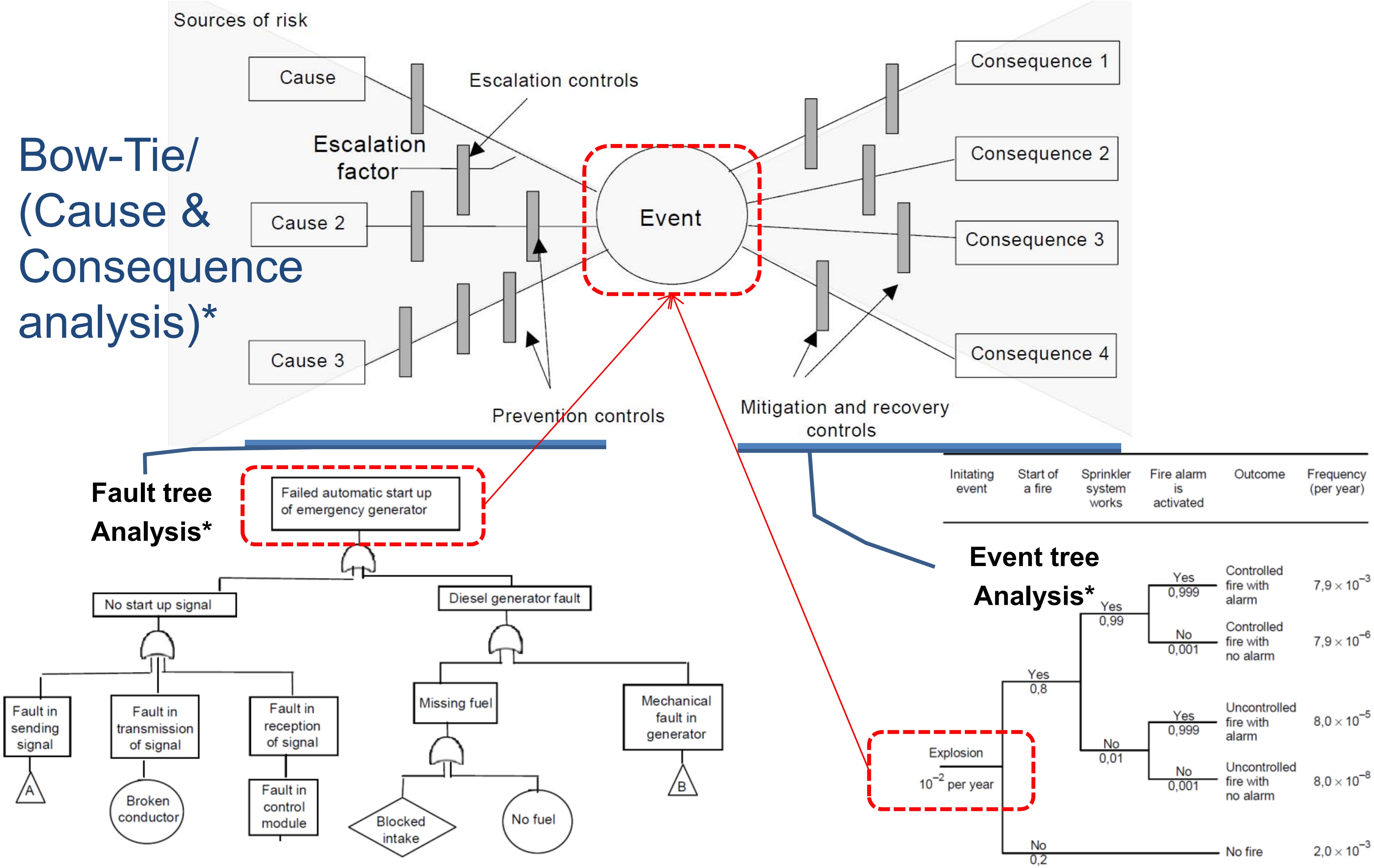
3. Risk Management – quantifying 'event prob.' & interdependency



*IEC/ISO 2009. IEC/ISO 31010 Risk management - Risk assessment techniques Edition 1.0 2009-11.

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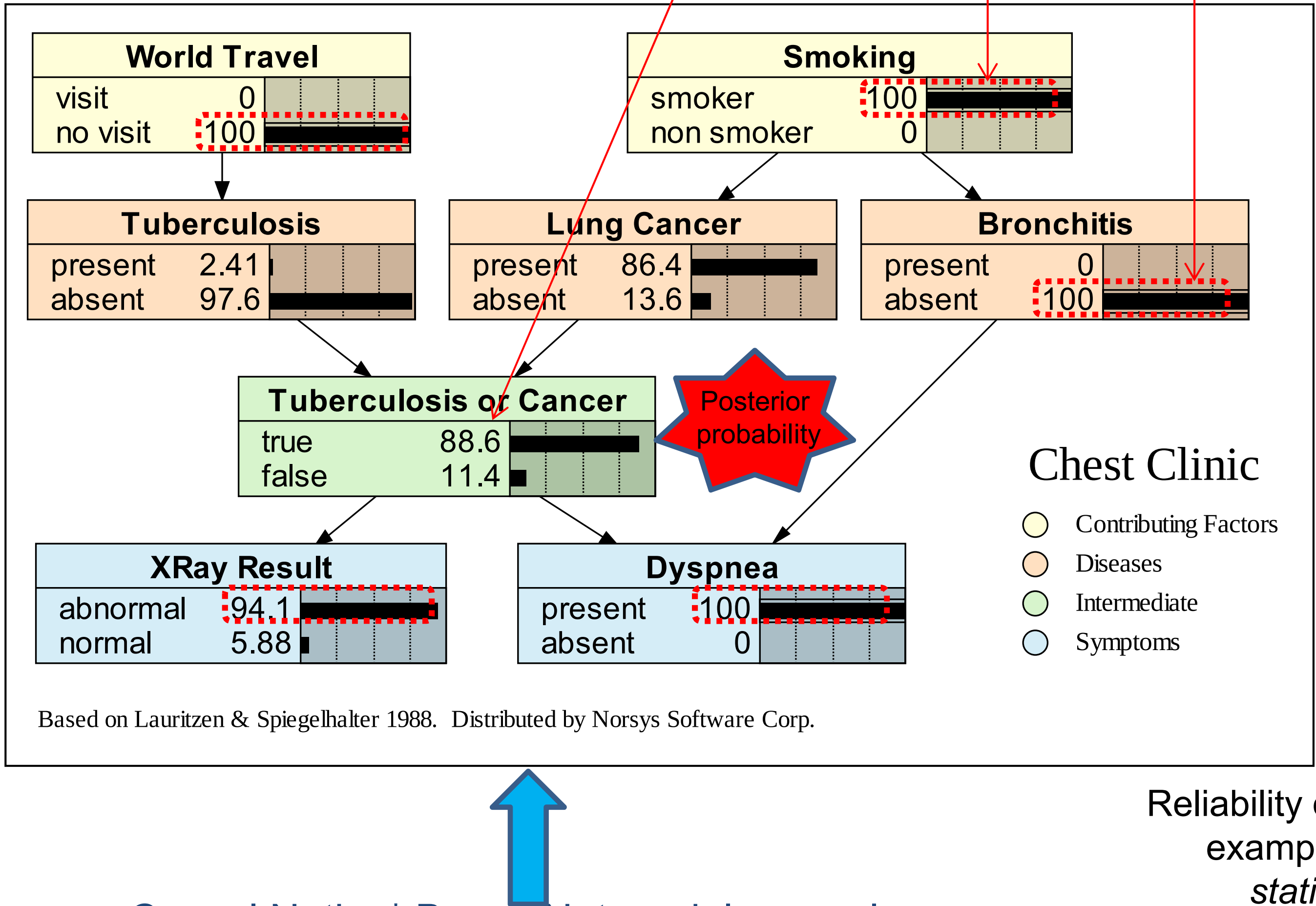
How to model interdependency: Bayes Nets?

Model aim: estimate cancer prob. after questions & tests



Causal Netica* Bayes Net model example

Some BNs relevant to solar storms

CODETTA-RAITERI, et al. 2012. Engineering Applications of Artificial Intelligence, 25, 683-697.
A dynamic Bayesian network based framework to evaluate cascading effects in a power grid.

DIGGINS, Z. J., et al. 2015. IEEE Transactions on Nuclear Science, 62, 1674-1681.
System health awareness in total-ionizing dose environments.

Reliability of model assessable using for example *Prediction accuracy, Kappa statistic, Area Under Curve /ROC, True/false positive/ negative rates*

Can management rely on 'The Market'? The financial discounting* conundrum?

- Government provides guidelines… but 'willingness to pay'?
- Climate change experience suggests management of events with ARIs > 20 y hard to mobilise
- Downstream flood event ARI>100 y too low to drive management. Discounting theory issue? Consider Houston recently.

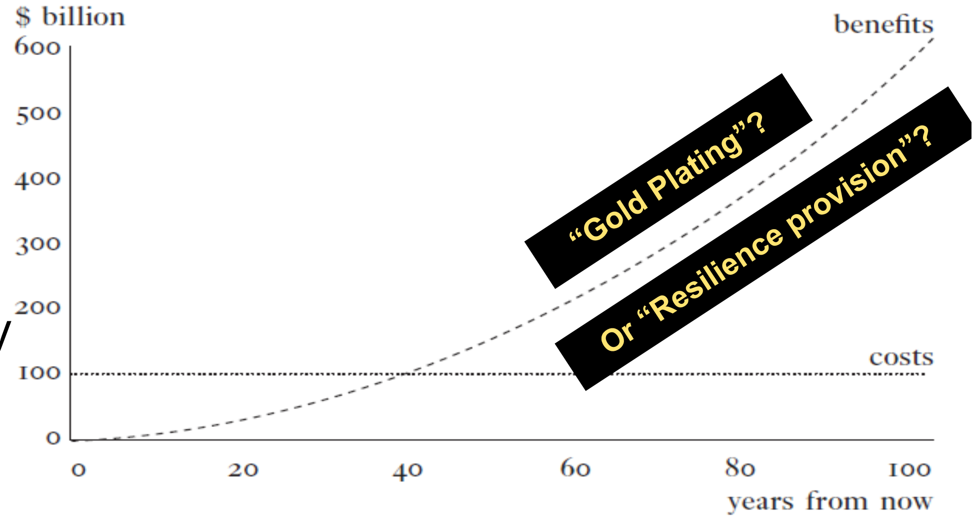


Figure 2.1 Costs and benefits, by year

[(? Similar market driver constraints with satellites, communications and electricity infrastructure ?)]

[Like LED globes? (lifetime <<50,000 h)]

*ACKERMAN, F. 2009. Can We Afford the Future? The Economics of a Warming World, Zed Books Ltd, Cynthia Street, London.

Conclusions

- **Risk management tools and theory offers analysis approaches**
- **Bayesian inference & nets are option for identifying priorities & exploring interdependency**
- **(some) Research should explicitly support risk decisions**
- **Economic behaviour may hinder risk management**

Or to put another way

"As I hurtled through space, one thought kept crossing my mind - every part of this rocket was supplied by the lowest bidder." #

 # Attributed variously to John Glenn and Alan Shepard

Policy>>>

Policy and decision support?

Suggested 1° infrastructure (incl. H_2O) sector response?

Rescue by cavalry (light brigade) may not be option…

1. Quantify *Fn*[solar storm probability=>consequence] (s)
2. Define "Tolerable Risk" levels for "Keystone" technologies must meet.
3. Detail Keystone sector failure ARIs, identify 'Grandfathering' issues.
4. Assess current & required infrastructure resilience levels (FTA/ETA).
5. Identify and implement reliability assurance methods e.g. contracts.
6. Validate, verify and audit all of the above, transparently.
7. Systematically research* & enhance risk management.

(Or 8. ignore issue & leave the market + federal 'policy' manage things?)

Questions?

* SCHRIJVER, C. J. et al. 2015. Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS. Advances in Space Research, 55, 2745-2807.