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Terms, Definitions and Concepts Related to Critical Infrastructures, Chokepoints & Services

RESIN Working Paper: January 24, 2010

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Abstract:

What are: interdependent, interconnected and interactive critical infrastructures systems? Chokepoints and the relationship to I₃CIS? What for that matter are their “interactions,” “resilience,” and “sustainability?” In giving initial definitions and descriptions of these concepts and terms, other issues related to the RESIN conceptual model, its eco-infrastructure element, and the probability and consequences of infrastructure failure are also addressed.

(This paper is an undated and revised version of Emery Roe’s 2009 sub-report for the RESIN project.)

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The focus of this paper is on identifying and understanding the unit of analysis, “chokepoints within an I₃CIS,” where I₃CIS means interdependent, interconnected and interactive critical infrastructure systems. My findings regarding terminology, definitions and concepts are presented in two parts: What is an I₃CIS? What is a chokepoint and how does it fit into an I₃CIS?

I: What is an I₃CIS?

Summary

One RESIN product is to be a conceptual model of the I₃CIS in the Sacramento Delta. Although fragmentary or infrastructure-specific models exist at more general levels, no region-specific inter-infrastructure I₃CIS model has been found to date (January 25, 2010), either in the published literature or as a result of contacting Delta experts.

Once developed, that model can be the basis from which we chose a subset of infrastructures (in whole or in part along with their interactions) as the I₃CIS of interest and a subset of those interactions in that I₃CIS as the chokepoints of interest.

I first review the literature on I₃CIS models generally, and then the existing empirical work on what have been found to be major interactions across infrastructures. After that, I present the preliminary I₃CIS model of the Sacramento Delta, based on the theoretical and empirical findings and site-specific features that drive infrastructure interactions in the Delta.

I conclude by discussing the concepts of “eco-infrastructure” along with further considerations about the probability and consequences of infrastructure failure (Pf and Cf), and how they relate to the Delta I₃CIS conceptual model.

Preliminary review of I₃CIS definitions and models

I₃CIS definitions. Critical infrastructures are assets and systems essential for the provision of vital societal services and include large engineered supplies for water, electricity, telecommunications, transportation and financial services (NRC 2009). RESIN focuses on the cross-infrastructure interactions at the I₃CIS level of analysis in light of the individual critical infrastructure systems (CIs) that are the components of the I₃CIS in question.

Before turning to I₃CIS models and theories of I₃CISs, two definitional points are important: What are the CIs and what is meant by their “interactions” at the I₃CIS level?

The US Department of Homeland Security has identified 17 critical infrastructures and key sectors: Agriculture and Food; Banking & Finance; Chemical; Commercial Facilities; Commercial Nuclear Reactors, Materials & Waste; Dams; Defense Industrial Base; Drinking Water & Water Treatment Systems; Emergency Services; Energy; Government

Facilities; Information Technology; National Monuments & Icons; Postal & Shipping; Public Health and Healthcare; Telecommunications; and Transportation Systems.¹

While long, the list is not unique. The European Union has identified eleven critical infrastructures: Energy; Nuclear industry; Information, Communication Technologies (ICT); Water; Food; Health; Financial; Transport; Chemical Industry; Space; and Research Facilities (European Programme for Critical Infrastructure Protection 2006). Some lists of EU critical infrastructures also include: Civil Administration and Public Legal Order & Safety (Boin et al 2006), for instance. While imperfect, the overlap in sectors between the US and EU lists is considerable.²

The upshot is that there are many critical infrastructure systems to be concerned about and that, in theory, the more CIs there are, the more varied interactions between and among them at the I₃CIS level.

What then is as an “interaction?” Start with two rudimentary distinctions in the literature.

First, interactions can be dependent or interdependent (Nieuwenhuijs, Luijff and Klaver 2008). A dependent interaction is primarily or exclusively one-way, where a change in one infrastructure leads to a change in another infrastructure (which in turn can lead to a change in a third infrastructure and so on):

$$\Delta CI_1 \rightarrow \Delta CI_2 \rightarrow \Delta CI_3$$

An interdependent interaction, in contrast, is a two or more way interaction, where a subsequent change in one infrastructure feeds back into newly changing the infrastructure whose initial change had affected it, i.e.,

$$\Delta CI_1 \rightarrow \Delta CI_2 \rightarrow \Delta CI_3 \rightarrow \Delta[\Delta CI_1 \text{ and/or } \Delta CI_2]$$

The differences between dependent and interdependent interactions explains why the “I” in I₃CIS is not just “interdependent.” Sole use of the latter term could lead some to conclude, erroneously, that we are excluding from analysis dependent, one-way interactions between and across critical infrastructures.³ A graphic representation of the important distinctions between dependent and interdependent interactions when it comes to the levee system is found in [Annex 1](#).

¹ Accessed online on June 10, 2009 at http://www.dhs.gov/xnews/gc_1179776352521.shtm

² One virtue of these long lists is that the DRMS Infrastructure Survey covers many of the items: “The Delta infrastructure can be divided into linear and point assets. Linear infrastructure includes railroads, highways, shipping channels, transmission lines, aqueducts, and gas and petroleum pipelines. Point infrastructure includes bridges, marinas, natural gas fields/storage areas, natural gas wells, commercial and industrial buildings, residences, and pump stations” (DRMS, Impact to Infrastructure 2007, p.3).

³ It is for such reasons that the UCB RESIN Project has termed its inter-infrastructural level of analysis as I₃CIS, interdependent, interconnected and interactive critical infrastructure systems.

A second set of distinctions is also important. Dependent and interdependent interactions can be categorized as spatial or functional. As Rae Zimmerman (2004) puts it,

Two ways that different infrastructure sectors can be connected or interdependent are spatially or functionally. . . Spatial dependency refers to the proximity of one infrastructure to another as the major relationship between the two systems. Functional dependency refers to a situation where one type of infrastructure is necessary for the operation of another, such as electricity being required to operate the pumps of a water treatment plant. . . The two categories selected here (spatial and functional) encompass most of the elements of the Peerenboom, Fisher and Whitfield typology. Spatial is equivalent to the geographic category and functional combines physical, cyber and logical.

Spatial and functional can occur and interact together, as when a levee breaches taking out the adjacent power line which in turn leads to a cascade of power line failure well beyond the levee system. I return to this topic in Part II's discussion of a chokepoint.

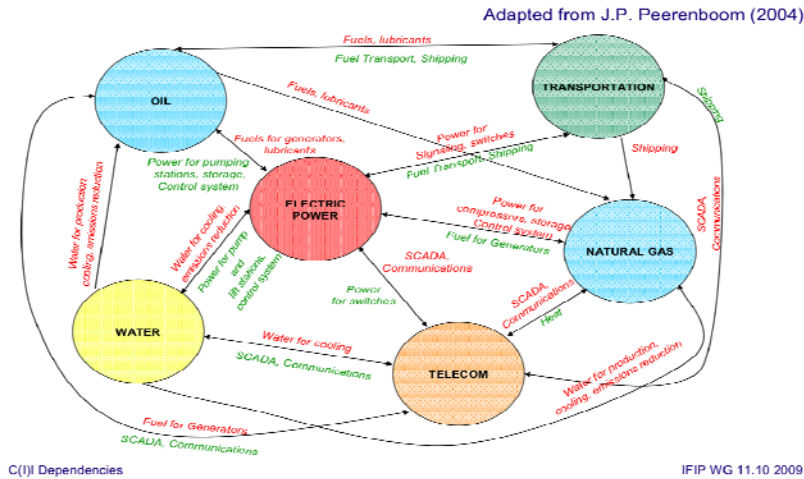
Zimmerman's last point is noteworthy: Many ways exist to categorize the interconnections of CIs at the I₃CIS level. We may find empirically that it is important to go further than a spatial/functional divide in our Delta work. Given so many different CIs, it is probably better to keep the interaction distinctions as simple as possible at the outset.

To summarize, the spatial and functional interconnections may be uni-directional (indicating a dependency) or reciprocal (indicating an interdependency). The levee breach can destroy the telecommunications tower behind the levee, but not vice versa. On the other hand, the destruction of that tower could bring down phone service, thus making it difficult or impossible to recover from that breach or prepare for another one later on

I₃CIS models. No overarching, accepted theory of how CIs are interrelated at the I₃CIS level exists. There are, however, conceptual models from basic to sophisticated.

The most frequent conceptual model is attributed to James Peerenboom, Director of the Infrastructure Assurance Center at Argonne National Lab. Below is an adaptation of the that model and the high degree of interdependence it presupposes:

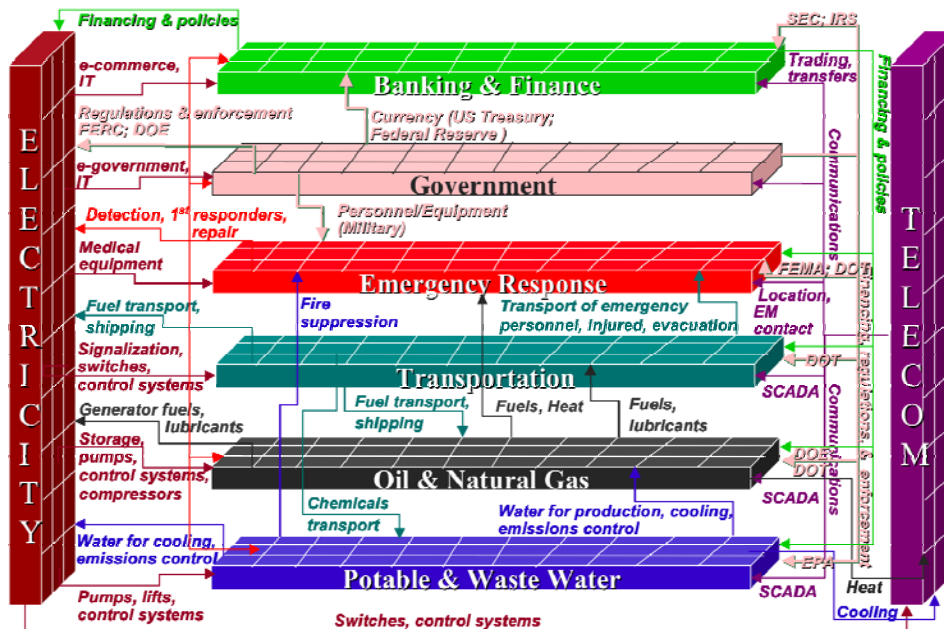
Around 2000 ... everything “interdependent”



(reproduced from Nieuwenhuijs, Luijff and Klaver 2008)

Among its shortcomings, this model makes it difficult to determine what, if any, critical infrastructures are more important, thus implying that in this cat’s cradle of interconnectivity everything is potentially equally significant.

Peerenboom’s model seems related to an early conceptual model of interinfrastructural connections developed by Miriam Heller, who was instrumental in the National Research Council 2002 report, *Making the Nation Safer*. Here, however, differences between infrastructures move to the foreground:



Interdependencies between eight critical infrastructures (Heller 2002)

In Heller's conceptual model, the cat's cradle of interconnectivity remains, but framed by the two bookend infrastructures of electricity and telecommunications. Note the connection between the two infrastructures is "Switches, control systems," an interface we return to later.

I₃CIS conceptual models have become considerably more complex since 9/11. The examples are numerous, but I limit myself to two that illustrate current trends.

Below is a conceptual model, using System Dynamics modeling, of interacting US critical infrastructures from Min, Beyeler, Brown, Son and Jones in their 2007 article, "Toward modeling and simulation of critical national infrastructure interdependencies,"

Modeling and simulation of infrastructure interdependencies

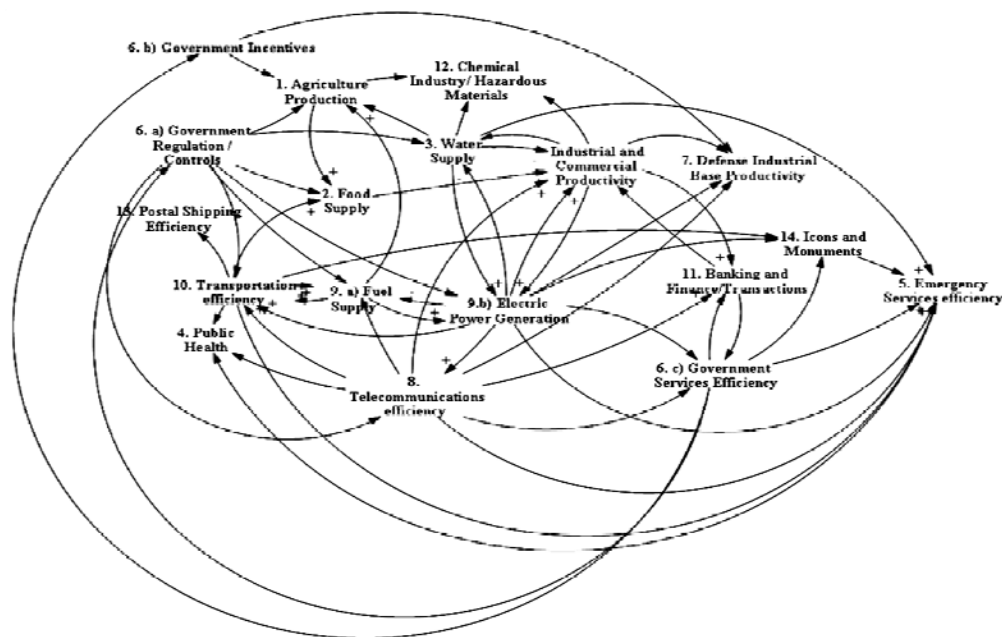


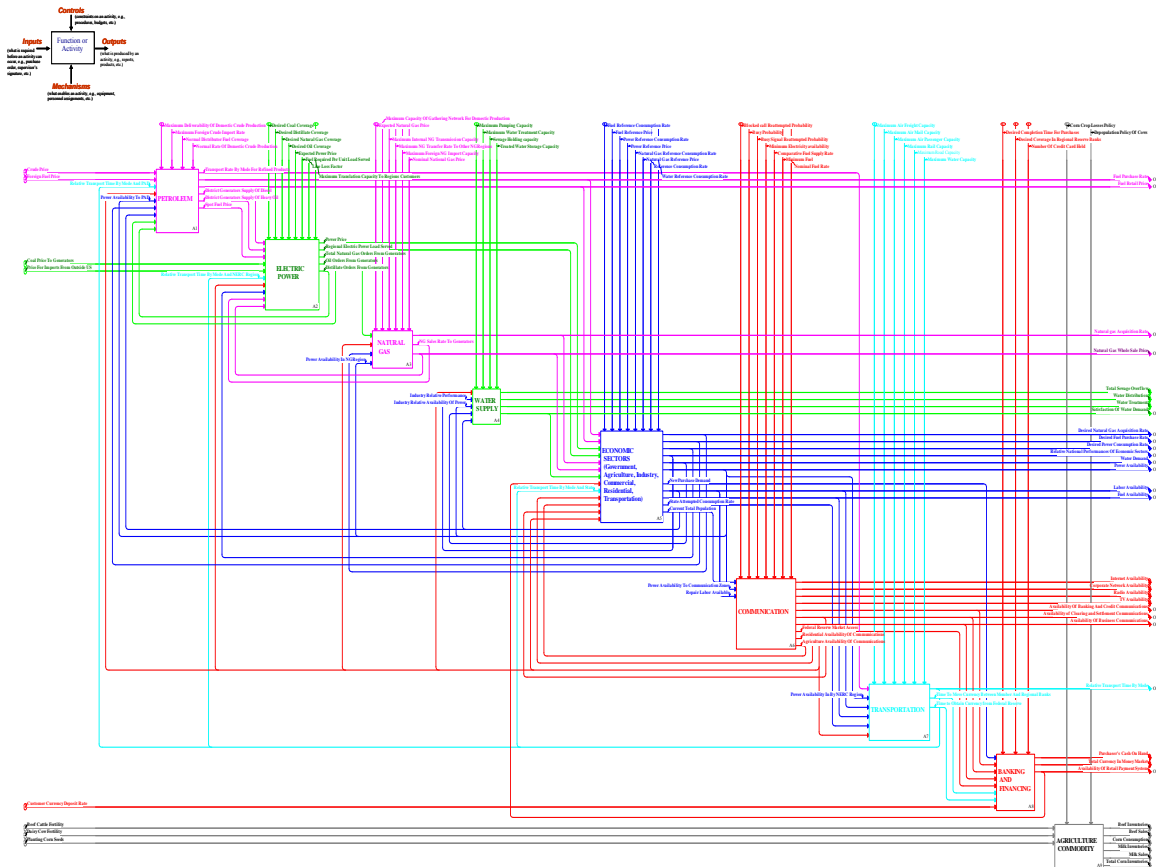
Fig. 1. Infrastructure interdependency.

The figure's numbered nodes correspond to the aforementioned DHS classification of US critical infrastructures and resource systems. Note many of these "interdependencies" are in fact what were identified earlier as primarily one-way dependent relationships, as in "Government Incentives" affecting "Agricultural Production."

When a Systems Dynamic approach is used, the interconnections can become considerably complex (for a powerful application in the water management area, see Deegan 2007). Go to the website for the National Infrastructure Simulation and Analysis Center (NISAC) at Los Alamos and Sandia National Labs, and you will find multiple publications applying this and other modeling approaches to US critical infrastructures in their entirety or by important components (e.g., power and electricity).⁴

⁴ Accessed online on June 10, 2009 at <http://www.sandia.gov/nisac/index.html>

Below is reproduced NISAC's representation of the nation's critical infrastructure interdependencies (from Min, Beyeler and Brown 2006). It is not possible for the human eye to read this figure unless you zoom to 350%. Its unreadability, however, gives an idea of the complexities involved, even when the critical infrastructures are reduced to a "manageable" number as show in the figure.



The conclusion to be drawn is straightforward: *YOU CAN MAKE I₃CIS CONCEPTUAL MODELS AS COMPLEX AS YOU WANT*. Modeling and computing power ensure that.

Why, though, would you want to make any I₃CIS model more complex, if all these interconnections are not found to be equally "important" in the empirical sense?

Empirical work on I₃CIS interactions

I have found only two empirical studies on cross-infrastructural inter-connections. Both underscore that in practice fewer dependent and interdependent interactions are present than the current I₃CIS models indicate are possible in theory.

The first study was published by Rae Zimmerman in a 2004 article, "Decision-making and the Vulnerability of Interdependent Critical Infrastructure" (Director of the Institute for Civil Infrastructure Systems at New York University, she is also a professor there).

Zimmerman compiled a purposive (non-random) database of failures and sequence of failures across major infrastructures and reported in a variety of venues for the period 1994 -2004.

The structures included: electric lines, fiber optic/telephone, gas lines, oil pipelines, sewers and treatment, street lights, transportation (bridges, rail, roadways, tankers), water mains, and other structures. The examples appear to be primarily from the United States, though not exclusively. She then analyzed the data in terms of what infrastructure failures caused failures in other infrastructures, finding that:

Table 1. Effect Ratios

1 Type of Infrastructure	2 # of Times Infrastructure (Column 1) Caused Failure of Other Infrastructure	3 # of Times Infrastructure (Column 1) was Affected by Other Infrastructure Failures	4 Ratio of Causing vs. Affected by Failure (Col. 2 divided by Col.3)
Water mains	34	10	3.4
Roads	25	18	1.4
Gas lines	19	36	0.5
Electric Lines	12	14	0.9
Cyber/ Fiber Optic/ Telephone	8	15	0.5
Sewers/ sewage treatment	8	6	1.3

(from Zimmerman 2004)

As the figures show, water mains caused more failures in other infrastructures than the reverse. In contrast, failures in gas lines were more likely to be caused by other infrastructure failures than be the initiator of failure elsewhere. Zimmerman also found that certain combinations of failures were more pronounced than others:

Certain types of infrastructure were frequently linked with one another, whether they caused or were affected by infrastructure failures. This database showed that the most likely combinations, in decreasing order of the number of events were: gas lines and roads (16), water and gas lines (12) electric and water lines (10), and electric and gas lines (7). This may simply be a function of how frequently these facilities are co-located, or alternatively, may reflect unintended interactions that occur when these facilities are subject to external stress.

Zimmerman's last point about the failure due to co-location of structures or external stress that affects all structures independently is especially important for our Delta modeling. For our purposes, also note the importance of water, roads, gas and electricity in these combinations.

The second study is more ambitious and recent. This database covers cross-infrastructure cascades and is compiled by the Dutch research body, TNO Defence, Security and Safety and the Delft University of Technology (TNO 2008). As of September 2008, the TNO

database covered 2650 critical infrastructure (CI) disruptions in 164 nations with 1090 cascading outages.

Their following table records the subset of 1749 CI failure incidents in 29 European nations, where an incident, when not independent and isolated, could initiate a cascade in the critical infrastructure or result in a cascade in another infrastructure:

CI Sector	Cascade initiating	Cascade resulting	Independent	Total	Sample size
Education	0	3	1	4	4
Energy	146	76	388	609	590
Financial Services	1	26	33	60	60
Food	0	4	3	8	8
Government	2	40	26	68	67
Health	1	16	22	39	39
Industry	5	15	7	27	27
Internet	15	51	95	161	160
Postal Services	1	0	0	1	1
Telecom	69	125	114	308	295
Transport	19	128	276	423	422
Water	9	18	51	78	76
Total	268	501	1017	1786	1749

Table 1: Categorization of number of CI disruptions events (TNO 2008)

Note the majority of incidents are isolated within the infrastructure concerned (1017 versus 769). The TNO study concludes: “Our analysis of the collected data shows that most cascades originate from only a limited number of critical sectors (energy, telecom) *and that interdependencies occur far less often than most theoretical studies assume*” (my italics).

Note the importance once again of electricity and telecoms in a cross-infrastructure perspective. According to the TNO summary,

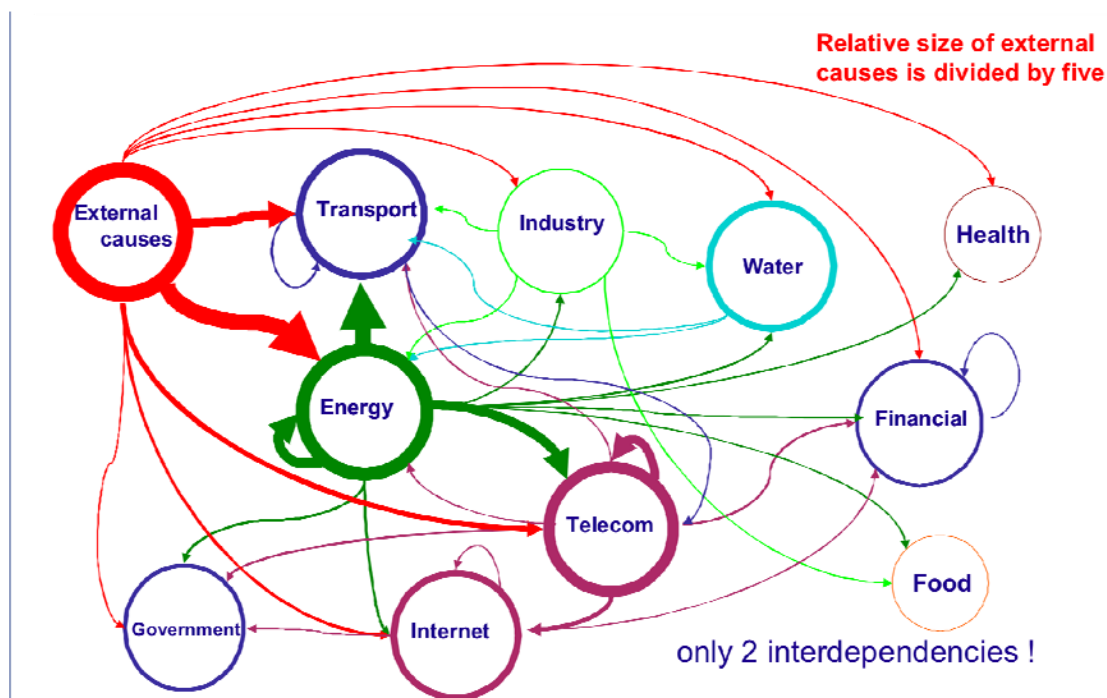
Energy and telecom are the main cascade initiating sectors (60% and 24%; see Table 1). Transport (5%) and water (3%) follow. The energy sector initiates more cascades than it receives. Interdependencies occur very infrequently: only two weak cases were recorded. Fixed telecom disruptions affect ATMs and electronic payments (financial sector), the mobile phone base stations - base station controller links, governmental services, and internet and telecom services. Within the energy sector, most dependencies (61) occur between power generation, transmission and distribution.

The authors of another study based on the TNO database—Eric Luijff, Albert Nieuwenhuijs, Marieke Klaver, Michel van Eeten and Edite Cruz (forthcoming)—draw out the important management implications of the Table 1 for critical infrastructures [CI]:

[W]hile the current literature gives very little clues as to the probability of cascading

failures, our empirical data suggests that such cascades are in fact fairly frequent. This forms a sharp contrast with the typical examples of events of low probability and high consequence that are often presented as evidence of the urgency of dealing with CI dependencies. Second, they question the validity of the Domino Theory of CI. While there are an almost unlimited number of dependencies and interdependencies among CI possible, i.e., there are many pathways along which failures may propagate CI sector boundaries, we found that this potential is not expressed in the empirical data on actual events. The cascades that were reported were highly asymmetrical and focused. The overwhelming majority of them originated in the energy and telecom sectors. This is not unexpected, but what is new is the fact that so few cascades took place in other CI sectors. Third, interdependencies occur far less than analysts have consistently modelled. We found only two cases on a total of some 770 CI failures. In short, while dependencies and interdependencies exist everywhere, they rarely appear to be strong enough to trigger a reported serious cascading CI outage.

It is this last finding—far fewer interdependencies than expected based on theory—that leads the TNO/Delft University of Technology team to propose their own database-specific conceptual model at the I₃CIS level:



In this model, the external causes are clearly the important initiator of cascades in individual CIs. “Drawn to scale” and based on empirics, their I₃CIS conceptual model recapitulates the importance of Energy and Telecom in terms of not only the number of initiating or resulting cascades, but also the interdependent feedback from one to the other and back again on itself has been more than amply documented. Most relationships,

as documented, are in fact one-way causal dependencies.⁵

Preliminary Delta I₃CIS conceptual model

It would be just as rash to draw conclusions for a Delta I₃CIS model from two empirical studies of cross-infrastructure interactions, as it would be to insist that national I₃CIS conceptual models, like those NISAC, should serve as the template for developing the Delta model.

That said, the above findings are suggestive:

- Electricity and Telecoms are probably more central to the operation and failure of critical infrastructures than these other infrastructures are, along the lines of the Heller model.
- However, external stress factors, combined with co-location of structures, constitute important causes of single and joint infrastructure failure.
- Water related failures need not insignificant and can become major when occurring next or near to other structures (co-location).

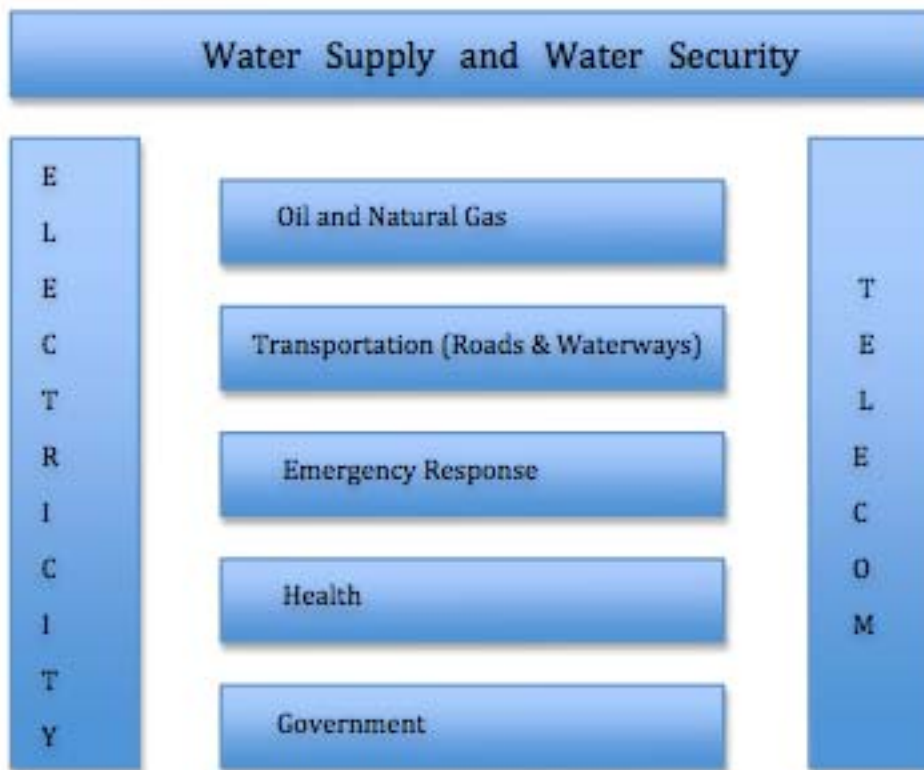
With these suggestions, I have taken two passes at developing the Delta conceptual model, each in light of more information.

As the first pass, it is seemed plausible that the preliminary Delta I₃CIS conceptual model would be:

- centered around levees prone to storms, earthquake and rising sea levels (external stressors),
- where the levees themselves protect major (regional and statewide) electricity and telecommunication structures whose point of interaction are their respective control rooms and operations units,
- and where other major infrastructure including roads, gas lines and major emergency responders are co-located with the levees, and
- which, if a cascade of dependent interactions were set into play, immediate issues of health of the remaining population and available government capacity would rise to the fore.

The first-pass conceptual model, without the yet-to-be-specified interconnections, is set out below. Here water supply and security are the overarching lintel, electricity and telecoms the primary ends, with other infrastructures the shelves or slats:

⁵ In case this point needs further support, Charles Perrow, the sociologist and theorist in the field of tightly coupled, complexly interactive systems, concludes in his analysis of case studies: “It is a commonplace that we live in a highly interconnected society, but in the case of disasters the connections are largely ones of dependency rather than *interdependencies*” (Perrow 2007: 296).

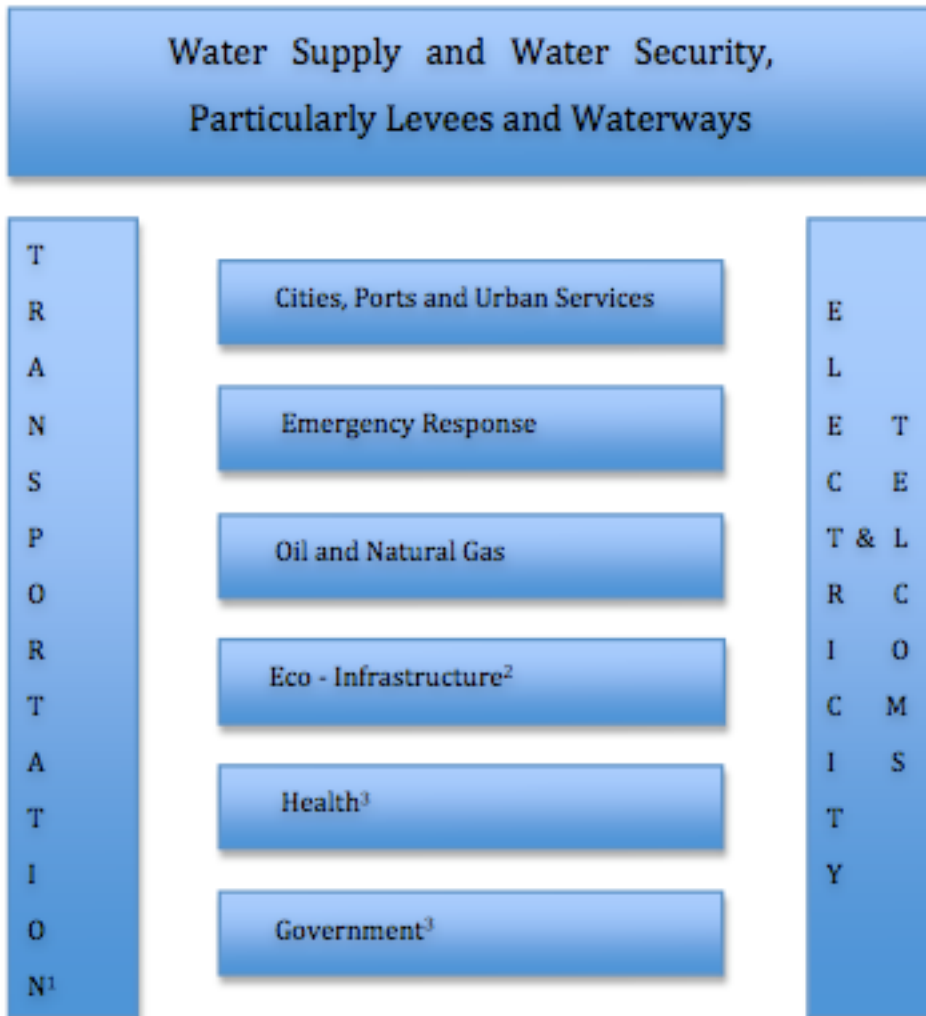


This first-pass model was subsequently revised in light of discussions with lead personnel in the development of the Delta Risk Management Strategy. Based on their experience in the Delta, they felt the initial model missed the importance of transportation in and around the Delta, primarily the importance of roads but also of shipping lanes, ports and the cities that circumscribe the region. It also became clear that the RESIN focus on ecology in the Delta could be analyzed, if only in part, around the importance of Suisun Marsh and other wetlands as an “eco- infrastructure,” that is, wetlands for important ecosystem services of water purity, fish habitat and flood protection to the region.

The engineers also mentioned non-levee system impacts of a disturbance, such as an earthquake or storm. It was possible to imagine disturbances that left levees without breaches but took out electricity for a drawbridge, thereby leading to transportation blockages throughout the region, including the Sacramento and Stockton ports.

These considerations led to revising the model into a second-pass version, which remains preliminary as well in light of the absent interconnections between the governing infrastructures:

**CONCEPTUAL MODEL FOR
INTERCONNECTED CRITICAL INFRASTRUCTURES IN THE SACRAMENTO DELTA**



1. Includes roads & deepwater shipping channels

2. Ecosystem habitat, such as Suisun Marsh

3. Based on expert opinion and reports

The second-pass model has been used in interviews with water and power in order to refine the model as well as generate real-time or near real time scenarios for I₃CIS interactions in the Delta. To date these interviews suggest that “Natural Gas” be combined with “Electricity” to form a bookend of “Power” along with Telcoms.⁶ While

⁶ In combining electricity and telcoms, we may be highlighting what is an underlying “cyber-infrastructure” without which these two infrastructures could not operate. If so, research as to interactions within this “meta-CIS” would take us to the national security level and into private sector business continuity plans. Understandably, however, management for cybersecurity of the Greater Bay Area and Northern California are, in important respects and as elsewhere, confidential.

further interviews are needed, we are now confident that the interviews continue to focus on those “switches and control systems,” i.e., the control rooms and operations units of the power and water infrastructures relevant to the Delta.

Note that, as primitive as the conceptual model is, it differs substantially from current models of how, e.g., a seismic failure would affect the Delta. Consider the following DRMS model,

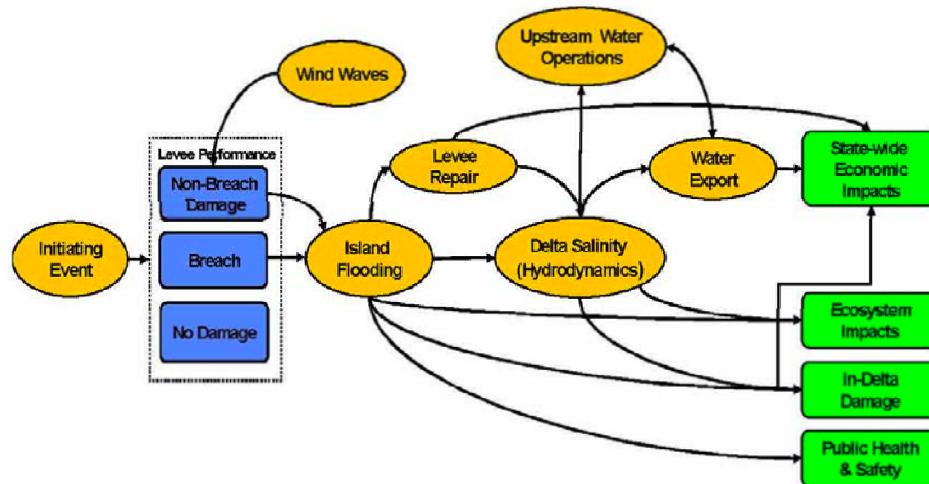


Figure 4-1 Influence diagram illustrating the basic elements of levee performance, repair, and Delta hydrodynamic response after a seismic event

In the above figure, which was compiled for different reasons than RESIN’s, the I₃CIS interconnections are collapsed under the green rectangles on the right showing impacts of an initiating event, in this case a levee breach. RESIN requires making these impacts and their consequences explicit in terms of interactive Pf and Cf (more in a moment).

Part I concluding issues

During the end of 2009 and into 2010, RESIN is examining spatial interactions at major co-located structures on Sherman Island. The RESIN conceptual model and associated scenarios has given us a better idea of the mixed spatial/functional interactions during our preparation for and actual site visit on Sherman Island in November 2009.

Using the conceptual model during our RESIN team site visit, we found a number of reported cross-infrastructure interactions at and around Sherman Island, including: when levees breach, port traffic on the shipping channels is said to close; if levees breach, Hwy160 will go, leading to congestion on the highways 80 and 4; eco-infrastructure in

the form of a berm was said to help protect an otherwise vulnerable levee stretch at an Island chokepoint; storms have taken out distribution lines, so residents do not have electricity for night pumping to dewater the island during a storm or overtopping event; power lines had to be raised because of shipping traffic; the Island drawbridge was said to have failed, thereby affecting traffic; a ship was said to have clipped a PGE gas line, and different companies' telcom lines said to be located right next to each other.

Once these and other cross-infrastructure interactions are mapped, it will be possible to produce a more fully informed conceptual model from which we can specify further just what I₃CISs we are interested in with respect to just what set of interactions we are calling chokepoints there (more in Part II below).

On another issue, note that the “eco-infrastructure” in the second-pass conceptual model mentions Suisun Marsh. While nearby, the marsh is not part of Sherman Island. However, the island does have bordering wetland areas that will be included in the 2010 RESIN analysis, particularly their positive and/or negative effects on adjacent levees.

A key implication of the RESIN conceptual model is this orientation to eco-infrastructure. Understandably, one might think that an initiative on resilience and sustainability, like RESIN, would treat the Delta ecosystem and environment as the background and context in which all the infrastructures of interest are embedded. Without a healthy ecosystem you cannot have healthy ecosystem services, including the infrastructures designed to provide them.

While RESIN is very concerned with that issue, we start the analysis by trying to understand how critical infrastructures protect and are protected by eco-infrastructure like wetlands.

As we saw in our November 2009, a wetland berm protected a major levee stretch that was itself an important part of a major chokepoint on the island. The conceptual model is formulated so as to find out not just how levees but also roads and telecommunications protect wetlands (in terms of reducing their time to recovery after a flood event) just as how wetlands protect levees and the roads and satellite towers behind them in terms of the latter's time to recover after a flood event. Once we have these interactions better specified we will be better positioned to move to the macro-level of analysis with respect to regional sustainability and resilience issues.

One last issue is important when it comes to the I₃CIS level of analysis. Once we have the RESIN conceptual model, we should also have a better idea about the nature of Pf, Cf and uncertainty at the I₃CIS level within the overall risk assessment and management (RAM) approach adopted in RESIN and its specific focus on a Quality Management Assessment System (QMAS) and a System Analysis Risk Assessment System (SYRAS). This in turn means having a better understanding of what examples (scenarios, chokepoints) are to be placed in the following table,

		<i>Scope of Interdependence</i>	
		Across a Single Critical Infrastructure (CI)	Within an I₃CIS of Multiple Critical Infrastructures
<i>Knowledge of Interdependence</i>	What We Know about Pf	E.g., one levee (or road, transmission line...) failing changes the Pf of others in the same system.	E.g., one levee (road, transmission line...) failing changes the Pf of other infrastructures within the same I ₃ CIS.
	What we know about Cf	E.g., infrastructure-specific replacement costs of one levee (road, transmission line...) affects replacement and repair costs of others levees.	I ₃ CIS-specific replacement and repair costs are affected by spatially and/or functionally linked infrastructures within or beyond specific I ₃ CIS.
	What we know about Uncertainty*	E.g., hazard of being unable to compute elements of Pf or Cf for the critical infrastructure.	E.g., hazard of being unable to compute elements of Pf or Cf for the I ₃ CIS.

*Defined as tight coupling and complex interactivity (Perrow 1984).

In short, one of the important features of QMAS/SYRAS as a RAM method is not only its focus on coming up with probability estimates, but also in isolating areas of uncertainty both at the CI and the I₃CIS levels of analysis.

II: What is a chokepoint and how does it fit into an I₃CIS?

Summary

A chokepoint represents *multiple* and *different* critical infrastructures (CIs) that are spatially or functionally interconnected. In ways that have yet to be operationalized, spatial means the different infrastructures in a chokepoint are adjacent or near each other, where the failure in one affects the failure of the other by virtue of their proximity. Functional means the operation of one depends on the operation of another (again in as-yet-specified ways), even if they are geographically distant to each other.

In other words, a chokepoint entails its own I₃CIS. Think of the chokepoint as a vertical I₃CIS column with an established circumference rising from below to above ground. In the case of the two Sherman Island chokepoints identified as a result of the 2009 site visit, the column rises from underground where the natural gas lines are, upward through the vulnerable stretch of levee, which is itself adjacent to a shipping canal and in one case a major road, and further into the air to where the power lines pass overhead and into the (variously polluted) air shed above.

Once we have selected the I₃CIS columns as chokepoints of interest, we can then follow where the intra-chokepoint interactions between spatially adjacent CI interactions lead functionally, even as this takes us further afield. Thus we can expect that Pf for the

selected I₃CIS of interest will have Cf that extend well beyond the Delta region for some or all of the CIs contained within the selected I₃CIS.

To capture these distinctions, I propose three types of chokepoints: Level I, Level II, and Level III chokepoint (CP), defined as follows in terms of their widening Cf_{cp}:

1. *Level I Chokepoint*: Cf_{cp} includes I₃CIS failure and CI failure beyond the selected chokepoint as spatially defined. For example, the Sherman Island levee breaches, leading to transmission line failure on and off the island; it causes the ports to be closed to traffic, leading to transportation problems and temporary business shutdowns throughout the region.
2. *Level II Chokepoints*: Cf_{cp} is potentially so large it is not possible to predict or compute these aggregate consequences, organizationally (e.g., in economic/legal terms) or technologically. For example, an unpredicted sequence of three levee breaches within the I₃CIS is so serious as to render it impossible to estimate their time to recovery and thus their full impact on selected CIs beyond the I₃CIS of interest.
3. *Level III Chokepoints*: Cf_{cp} is so massive as to constitute a “game-changing event.” For example, the complete disappearance of major Delta Islands (and their infrastructure) or the indefinite shutdown of the ports would threaten to break the Delta zero-sum game among stakeholders.

Aspects of *resilience* and *sustainability* within each level of chokepoints could then be described as follows:

- *Resilience* centers on Pf: The goal is to reduce Pf for an infrastructure within a chokepoint, thereby reducing overall Pf_{cp} for that chokepoint, e.g., by improving recovery time of the infrastructure in question.
- *Sustainability* centers on Cf: The goal is to ensure that Cf_{cp} of any chokepoint, should it still fail, does not increase the Pf of another spatially or functionally related chokepoint, e.g., by managing the Cross Delta Channel or Project pumps so as to accommodate the unpredictable effects of levee flooding.

A major implication of these partial definitions: *We make a very real advance in resilience and sustainability in and of themselves just by doing the GIS mapping of the selected chokepoint, e.g., a Greater Sherman Island chokepoint. Why? Because time to recovery—knowing the next steps ahead when bouncing back or absorbing a shock—and persistence of function—knowing how to respond to unpredictable change over time without worsening the function in question—require managers to know what the chokepoint is that they are returning to or having to change in order to ensure it persistence.*⁷

⁷ To be clear, these definitions of resilience and sustainability are incomplete and only part of the eventual RESIN picture. See Roe White Paper xx/10 for other aspects of resilience and sustainability.

Only that way, I believe, will we be able to come to the conclusion that some chokepoints, no matter how you look at them—from the Pf or Cf—simply may be resilient or sustainable, and we have an approach and methods to explain why.

Moreover, I believe, this approach—developing the conceptual model first, then identifying the I₃CIS (infrastructures) and chokepoints (interactions) of interest (we already have guidance from the RESIN as to what they should be), thereafter undertaking analysis as to what kinds of chokepoints they are in terms of interactive Pf and Cf, and then concluding what the analysis means in terms of resilience and sustainability for the selected I₃CIS and its (types of different) chokepoints—provides a useful template for rethinking engineering education along the lines sought by RESIN.

Now to the details about chokepoints and the issues they raise.

Dual role of chokepoints

The term, chokepoint, sounds negative. Yet military strategy captures both the positive and negative side of a chokepoint: a deep valley on land or narrow strait at sea, which an attacking unit is forced to pass through but which the defending force takes advantage of. The chokepoint enables numerically inferior defenders to prevent larger superior forces in bringing their full combat power to bear. In this way, a chokepoint is negative from the perspective of party and positive from the perspective of the other.

So too does the infrastructure chokepoint have a dual role. The north-south high voltage transmission line in California, Path 15 has for years been a major chokepoint. One can imagine a disaster—human or other—taking the line out of commission, thereby threatening electricity in the state and beyond. Yet control room dispatchers responsible for defending Path 15 already focus considerable attention on that path precisely because it is a chokepoint. Chokepoints, in this sense, are the places where terrorists are likely to direct their attention, but they are also the places to which control room operators, with their trained competencies in anticipation and resilience, are most attuned.

The professionals who manage the grid have experienced a variety of hardships with Path 15—overheating which limits its capacity to carry power, congestion which blocks feeder lines into and out, as well as failures along sections of it caused by fires, storms, earthquakes and more. Managers and operators have fashioned multiple solutions to these problems—ranging from rerouting power along alternate paths, to calling on back-up generation in localized areas to strategic load reductions when necessary. The defenders are more prepared for a wider set of contingencies because Path 15 is so key to the State's electricity transmission. In other words, to view a chokepoint solely as a common mode failure (i.e., if it fails, a lot else fails) is too negative if that does not include the positive management features posed by being such a chokepoint.

Implications of dual role of chokepoints

This double-sided nature of chokepoints has surprising implications. Imagine, as has been recommended, that you decentralized the California electric grid in order to reduce dependence on transmission lines like Path 15 (i.e., you see Path 15 as a point of common mode failure).

Doing so means the decentralized system now poses many more independent targets of potential vulnerability. Terrorists, to continue the example, could strike anywhere and, while they may not bring down major portions of the grid, they can still score their points in the psychological game of vulnerability. Under a decentralized grid, the local managers will also not have a clear picture of what's happening overall when the disaster strikes, nor will they have as wide a range of alternatives and recovery options currently under the more centralized grid.

In fact, you may have to *add* more chokepoints in order to take advantage of the putative benefits of a decentralized system. One option to improve an organization's computer network is to have multiple chokepoints. A common example: If all your traffic from the internet is routed through a single firewall (virtual private network, e-commerce, mail, FTP, and outbound traffic), then a frequent recommendation is that you consider another firewall, say, dedicated to the e-commerce and email functions only. In the same way, one part of the answer to Path 15 being a chokepoint has been to ensure that electricity flows east and west, not just north and south, in the State, along other major transmission lines (thus other chokepoints).

I cannot stress too strongly that the negative feature of chokepoints within an I₃CIS framework—tightly coupled, complex interconnections—can offer positive features to managers when resilience and sustainability are the goal (for more on the positive resources provided by tight coupling and complex interactivity, see Roe and Schulman 2008).

Checkpoint congestion and unpredictable Cf

Many bridges are only chokepoints during rush hours. In a single infrastructure system, the higher the “traffic” at one point relative to others in the same CI, the more likely that point will be a chokepoint in that CI. Conversely, a point where traffic is always low is not a major chokepoint within the CI in question.

The relationship changes when the chokepoint consists of multiple infrastructures, the interconnected critical infrastructure system (I₃CIS). Here a minor levee within the levee system (a minor point within a given CI) could be adjacent to an important generator, road and telecoms tower, thereby render this minor-CI levee into a very major piece of I₃CIS infrastructure.⁸

An I₃CIS chokepoint becomes a major bottleneck because one or more of its infrastructures fails and thereby “jams up” the operation of the other infrastructures spatially and functionally interconnected with it. The problem with this kind of inter-

⁸ Being unable to see how a minor facility within a CI can be a major facility within an I₃CIS is a good example of committing a Type III error. Only by managing at the I₃CIS level can you see what looks to be managing the right problem—the Delta levee system in terms of its own priorities—is actually managing the wrong problem—we should be focusing on the levees that are priorities because they are within major chokepoints. By managing the chokepoints with multiple CIs you would focus on the “right” levees to be managed. For some of the downside in doing so, see Roe White Paper xx/10.

infrastructure “congestion” at the chokepoint is the same as at the intra-infrastructure congestion—both have unpredictable (amplifying) ramifications and consequences, Cf.

This property of being unpredictably cascading can be considered a major feature of I₃CIS chokepoints, and one more reasons why we need resilience and sustainability. What would make Sherman Island itself a Level III chokepoint, for example, would be that if and when a levee breaches, the consequences would not only be unpredictable but incalculable thereafter.

In particular, it may not be possible to predict the Cf that can arise when the chokepoint fails, *even when we have reduced the chokepoint’s Pf through better design and management at the I₃CIS level*. In our earlier terminology, resilience may be possible but not sustainability.

This potential to become a “*game-changing*” *Level III chokepoint seems especially important to stress in any definition of an I₃CIS chokepoint*. For it is only within that macro level of analysis that we can raise key questions when it comes to sustainability and resilience.

Quite clearly, were Sherman Island to disappear, that would be a major disruption of the Delta. But would that disruption in the end be *on net* positive or negative? The I₃CIS framework forces us to ask and answer the question, Under what conditions would the disappearance (failure) of a major chokepoint, like Sherman Island, be a Good Thing when it comes to issue of a realizing more sustainable and resilience Delta region as its own I₃CIS? Just because we cannot fully compute Cf associated with a chokepoint failure does not mean that we cannot or should not be explicit about scenarios under which such a collapse might be, on net, beneficial.

Indeed, it is only at this level and in this way move beyond issues of “eco-infrastructure” whose resilience and sustainability depend on other supporting wraparound critical infrastructures to the wider issues mentioned earlier of how resilient and sustainable is the landscape and environment in which these infrastructures are embedded.

In fact, without these I₃CIS-wide scenarios of the positive and negative consequences associated with chokepoint failure, I doubt it will be possible to come to grips with what is, for me, a major question of the RESIN research: *Will we be able identify I₃CIS chokepoints that are in the end simply not sustainable or resilient, no matter if sustainability and resilience are associated with reducing Pf directly and/or compensating for the inability to directly control for Cf?*

Major caveats and a final question.

Even if we could agree on the units and levels of analysis in the I₃CIS, we would still face severe empirical issues. First, the I₃CIS may well be constantly changing both spatially and temporally. This indeed was the conclusion of the latest science review with respect to the Delta’s dynamic ecosystem (Healey et al 2008). It means that even if we agree on the small scale and large scale and on the short-term and the long-term, the I₃CIS may be changing so rapidly or unpredictably that we have little hope of thinking

long term from the small scale or think short term from the large scale (both of which are core to resilience and sustainability).

More to the point, stakeholders are *not* likely to agree on the requisite units and levels of analysis in an I₃CIS (this is the lesson of the Hanneman/Dyckman paper on the decisionmaking in the Delta⁹). In these ways—lack of stakeholder agreement combined by unpredictable changes combined with never enough money—means we have perforce defined the I₃CIS, at least on its own, as a system intractable to management.

Even if the conceptual model for an I₃CIS treated certain infrastructures as more important than others, such a stratified hierarchy would not necessarily make management at the I₃CIS level more tractable. Assume that electricity and telecoms are superior infrastructures as modeling and data suggest. Then the classic engineering and high reliability management response would be to ensure electric and telecom backup facilities and reserves are built out-of-Delta as fallbacks when their in-Delta counterparts fail. But who would build and pay for these reserves? One current recommendation is to authorize a special governing authority for the Delta to direct and coordinate I₃CIS level matters within the area. But would or could its powers extend to out-of-Delta I₃CIS developments?

For these and other reasons, management at the I₃CIS level of analysis rapidly begins to look something akin to the Mekong River Commission trying to arrange joint projects involving Cambodia, Laos, Thailand Viet Nam along with China and Burma. We quickly move into thinking of I₃CIS management as intractable.¹⁰

If so, then the obvious question is: *Given the long persisting zero-sum nature of the Delta politics and given the documented shortcomings of the major bureaucracies with overall*

⁹ The irony is that the most resilient and sustainable enterprise underway in the Delta is the ongoing stalemate there over its future. A 50-year old zero sum game that persists indefinitely is pretty much its own kind of “sustainability” (i.e., the stalemate goes on for decades) and “resilience” (it bounces back to a stalemate every time someone tries to change it), albeit in perverse ways.

¹⁰ Nothing in this subsection is intended to discourage the readers from pursuing their own I₃CIS level of analysis. The importance of thinking of Delta as place, ecosystem and crossroads has been a major feature of the recent Delta Vision exercise (Blue Ribbon Task Force 2008). In fact, one can think of other I₃CIS-level narratives about the Delta. I mention only two here: *Delta as buffer* and *Delta as palimpsest*.

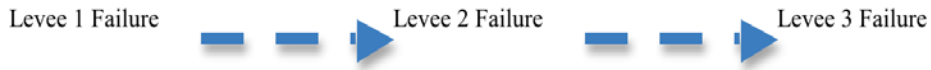
Delta as buffer is the story about how the Delta stops a metastasizing urbanization moving eastwards into the Delta from San Francisco and East Bay and westwards into the Delta from with Sacramento, Stockton and the line of cities and towns bounding the region on the west (much as agriculture in Southern Florida and Western Netherlands stop urbanization moving into the “green” areas of each). Delta as palimpsest is the story about how the Delta is a region overwritten by multiple narratives (e.g., place, ecosystem, crossroads, buffer, etc.), much as Canada has been described as a palimpsest or overlay of different classes and generations. Read from one direction, the Delta is a one story; read from another direction, it is all a different story, and so on, just like the optical illusion of a duck-rabbit, which can be seen as duck or as a rabbit, but never as both at the same time.

The list of other narratives about the Delta, not least of which are hybrids of those already mentioned, is I suspect a long one.

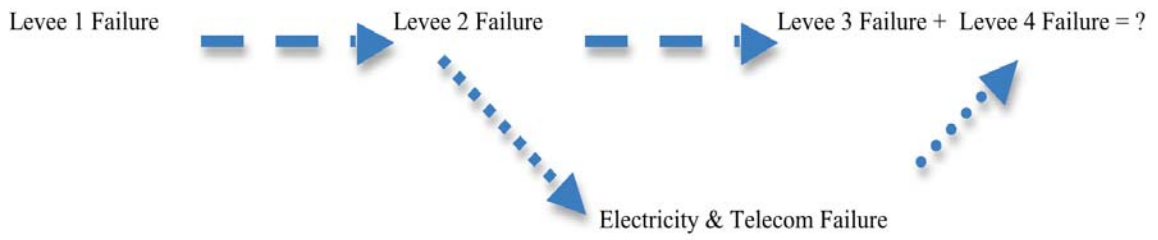
management of key infrastructure into and out of a dynamic Delta, and given the highly interconnected nature of these infrastructures, both at the theoretical and empirical levels, why ever then have services from these infrastructures remained more or less reliable up to this point?

Annex 1: Schematic of dependent & interdependent interactions involving levee system.

Within Critical Infrastructure



Across ICIS



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