State-space Structuring of Stakeholder-based Collaborative Environmental and Natural Resource Systems Modeling for Team-building, Database Organization, Systems Analysis, Scientific & Management Decision-making, and Outreach

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Three features . . .

1. Process vs. product

Modeling (including collaborative modeling) can be distinguished as

**Process** oriented vs. **Product** oriented

"Model-Making" vs. "Modeling"

Premise: The process side is underappreciated as having product-independent value in its own right.
Modeling Protocol
Compartment (stock & flow) models

Initiation/Specification
- purpose, need, scope, goals

Conceptualization
- compartments, connections, currency, controls

Formulation/Mathematization
- system equations, functional forms

Identification
- calibration/quantification

Simulation /Experimentation
- Validation, verification

Utilization/Application
- understanding, prediction, decision-making

Model-making PROCESS
- expert domain

Modeling PRODUCT
- modeler domain

science, applications, & management domains
Three features . . .

2. Formal structuring

The modeling process can be structured and formatted by formal theory.

State-space system theory is the form employed in IMM.
Properly institutionalized, the modeling **process** and its follow-on **products** can become permanent assets of user institutions, fostering a "bottom-up" basis for integrative science and management.

**SUMMARY:**

1. **Process** first, **products** later
2. Formal structuring by system theory
3. Institutional permanence
Team and culture building
Structures people interactions
Emphasizes the modeling process first, products later
Captures and organizes the knowledge state-of-the-art
Identifies areas of ignorance
Codifies knowns & unknowns
Motivates and formats databases
Counters the maxim, "Data banks don't bear interest"
Enables decision support
Guides research, management directions and priorities
Structures support ($$$) directions and priorities
Informs management decision-making
Aids communication among constituencies
Holds the place for continuing (perpetual) development

Overarching goal...
Team- & culture-building to holism
Further premise:

Initiation/Specification
purpose, need, scope, goals

Conceptualization
compartments, connections, currency, controls

Formulation/Mathematization
system equations, functional forms

Identification
calibration/quantification

Simulation/Experimentation
Validation, verification

Utilization/Application
understanding, prediction, decision-making

Iteration
modification

Formalizing this ...

PROCESS
expert domain

PRODUCT
modeler and science & management domains

My Message
1. Spring sabbatical  
Michigan State Department of Systems Science Program  
Course in state-space system theory  
Instructor: James A. Resh

2. NSF summer institute  
U. of Oklahoma Biological Station, Lake Texoma  
~40 college biology teachers, 8 weeks as conceptual model-makers, ecologically modeling a cove adjacent to the station; field work and computer usage were featured

3. Smithsonian  
Glover's Reef, Belize  
~40 of the world's leading coral reef experts; living in wind-blown thatched huts; sustained by snorkeling, diving, and rum cokes; spending 2 weeks as model-makers, making a conceptual model of the whole atoll ecosystem

1971—a seminal year

I have since studied all the mathematical system theories and settled on Zadeh's state-space theory for ecological purposes.
4. UNDP program

ADRIA—The Yugoslav Adriatic Coastal Ecosystem

In multiple week-long workshops over the ~5 year period, > 100 scientists of marine, fisheries, etc. laboratories and universities in the region conceptualized models of the region's ecosystems and water bodies. Over the course of this program, >10 conceptual models of water bodies, the atmosphere, and the economics of tourism were created. As far as I know, none of these models were ever institutionalized for further development or use by any of the participating laboratories.

ca. 1975—1980

5. @ UGA

Graduate teaching

Since these experiences, all my graduate courses have featured team-based modeling, simulation, and systems analysis.
6. NSF LTER program

Integrated Studies of the Okefenokee Swamp Ecosystem

Student researchers made multiple conceptual, and a few operational, models of different subsystems and processes in Okefenokee. It became impossible, however, to establish ongoing and model-making as NSF wanted to achieve uniformity across its sites, and no others were doing work with a strong modeling orientation. My stubborn commitment to modeling, and an ensuing struggle with NSF, caused loss of funding in 1986. The LTER sites, a prime target for IMM in the ecological world, are fragmented in their work still today— one of the program's most persistent criticisms. Culture-building by IMM is sorely needed in this domain.

7. Incorporation

Ecology Simulations, Inc.

We ran a few contracts. There was no market. Google won't find ESI for you today, but we are still on standby.
8. This is Dick Sage ...
Adirondack Ecological Center, Newcomb, NY

I collaborated with him 1-on-1 for eight years building "everything known about the Adirondack White-tailed deer" into a huge (~100 pp. of code) ecosystem-based Stella simulation model for this species

I succeeded in converting this straight-talking wildlifer-forester into a hemmer-hawer who could no longer give a straight answer to anything. He knew too much, and how it fit together. Dick's model-making experiences had transformed him from initial critic and skeptic into the world's first "systems-thinking wildlifer-forester"

On a weekend in early August, 2001 I finally closed the model around on itself and generated (without changing a single one of the several hundred parameter values Dick had computed and supplied) the target number of 15-20 deer/mi² on the Huntington Wildlife Forest (AEC)
Dick died two days later after collapsing on Whiteface Mountain leading a class field trip with Bill Porter. They were coming to meet me for a tour of a bog at Paul Smith's VIC.

He never knew we had finally graduated from modeling "process" to "product".

It wouldn't have mattered. For him the jury was already in on the value of a process he had once referred to as "a bunch of [expletive deleted]"

To date, no institution or wildlife management agency has claimed the model for further development and use. Nor would they. There is not yet a culture for this—that is still to be built, and hopefully this conference might become one of the steps in that very needed direction.
State-Space Determinism
Lofti A. Zadeh

Abstract Object
(open system)

\[ z = \text{input vector} \]
\[ x = \text{state vector} \]
\[ y = \text{output vector} \]
\[ Z = \text{input space} \]
\[ X = \text{state space} \]
\[ Y = \text{output space} \]

\[ \phi : Z \times X \rightarrow X \]
state transition function
\[ x = \phi(z, x) \]

\[ \rho : Z \times X \rightarrow Y \]
response (output) function
\[ y = \rho(z, x) \]
How State-Space Systems Work

Example: 3 states (x), 2 inputs (z), 2 outputs (y)

\[ Z = \{0, 0, 0\} \]
\[ Z = \{0, 0, 0\} \]
\[ Z = \{0, 0, 0\} \]

\[ x = \{I, II, III\} \]
\[ \phi(z, x) \]
\[ \phi(z, x) \]
\[ \phi(z, x) \]

\[ x = \{I, II, III\} \]
\[ \rho(z, x) \]
\[ Y = \{a, b\} \]
\[ t_0 = 0 \]
\[ t = 1 \]
\[ t = 2 \]

\[ \ldots \]
“4 C's” model construction
Digraph format

The "4 C's"
- Compartments
- Connections
- Currency
- Controls

methods involve,
- parsing & defining
- describing & documenting
- estimating & measuring

these model categories
How State-Space Systems Work

The state transition function is usually expressed in differential form . . .

\[ \phi': \frac{dx}{dt} = F_1 + z = F^T_1 + y \]

**State vector**

**Flow unit**

**Input vector**

**Output vector**

**OUTPUT ENVIRON**

Generating form (input driven)

**INPUT ENVIRON**

Generating form (output referenced)
The measurable intrasystem environments of all system components
Illustration

Hierarchical Categories
Four levels for working purposes

- Environment
- System
- Sector (Subsystem)
- Compartment

Compartment are focal
Teams form around sectors
The qualitative adjacency matrix, isomorphic to the quantitative flow matrix, is at the core of IMM state-space structuring.
Digraph → Adjacency Matrix → Isomorphism

\[ A = \]

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

orientation: columns to rows

\[ \text{IMM} \rightarrow \text{Structuring} \]
"4 C's" model construction
Adjacency matrix formatting for pairwise integration of compartment sectors

Donor Compartments
\((x_1, \ldots, x_n)\)

Recipient Compartments
\((x_1, \ldots, x_n)\)

Inflows

Outflows

Boundary inputs

Boundary outputs

Inputs
\((z_1, \ldots, z_n)\)

Outputs
\((y_1, \ldots, y_n)\)
The ABCD's of Environ Analysis
Mathematical Methods

\[ \phi' : \frac{dx}{dt} = F1 + z = F^T1 + y \]

Qualitative:
- Direct (m = 1)
- Indirect (m > 1)

Isomorphous quantitative modeling products follow

\[ D = B' - B, \quad U = \sum_m D^m = (I - D)^{-1}, \quad Y = U \cdot T \]
A Case Study
Brine Disposal Environmental Impact Assessment
and
Quantification of Ecosystem Health
by
Network Environ Analysis (NEA) in the Strategic Petroleum Reserve

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and
Ecology Simulations, Inc.

Athens, GA 30605, USA
INTRODUCTION

This study was scoped as a proof-of-concept project.

It was funded around 1980 by the National Oceanic and Atmospheric Administration (NOAA).

It addresses the natural complexity of whole ecosystems by Network Environ Analysis (NEA), a methodology that implements environmental system theory.

Its results and predictions have never been tested.
I. The Strategic Petroleum Reserve
THE STRATEGIC PETROLEUM RESERVE

Brief History & Current Status

**Provides for emergency oil storage**
most in salt domes along the Texas and Louisiana coasts

**Established by Congress in 1975** (PL 94-163) after 1973-74 oil embargo

- **Original provisions**
  - 150 million bbl by end of 1978
  - 500 million bbl by end of 1982

- **1978 amendment**
  - expansion to 1 billion bbl

**Current capacity 727 million bbl** (115,600,000 m³)

- **February 2012 inventory**
  - 695.9 million bbl (110,640,000 m³) = 36-day supply

**Four sites** near petrochemical refining and processing centers

- **Bryan Mound**—Freeport, Texas; capacity 254 million bbl
- **Big Hill**—Winnie, Texas, capacity 160 million bbl
- **West Hackberry**—Lake Charles, Louisiana, capacity 227 million bbl
- **Bayou Choctaw**—Baton Rouge, Louisiana, capacity 76 million bbl
The Louann Salt Formation, source of the salt domes, was deposited in the middle Jurassic 160-million years BP.
Louann salt, less dense than overlying sedimentary strata, rises upward from beneath the sea floor and land surface to form the salt domes...
THE STRATEGIC PETROLEUM RESERVE
Salt-Dome Storage Caverns
Operation Cycles

Each site contains a set of oil storage caverns solution-mined beneath the caprock surfaces

3 operating stages

#1 seawater pumped in, effluent brine out

#2 oil pumped in, brine pumped out

#3 seawater pumped in, displaced oil out
II. **Gulf Ecosystem "4 C's" Model**
GULF ECOSYSTEM MODEL

Compartments

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Pelagic Planktivores</td>
<td>N2</td>
<td>Benthoplanktivores</td>
</tr>
<tr>
<td>N3</td>
<td>Benthoires</td>
<td>N4</td>
<td>Type I Nektivores</td>
</tr>
<tr>
<td>N5</td>
<td>Type II Nektivores</td>
<td>N6</td>
<td>Type III Nektivores</td>
</tr>
<tr>
<td>N7</td>
<td>Type IV Nektivores</td>
<td>N8</td>
<td>Type I Mixed Feeders</td>
</tr>
<tr>
<td>N9</td>
<td>Type II Mixed Feeders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N10</td>
<td>Penaeid Shrimp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>Nannophytoplankton</td>
<td>P3</td>
<td>Microzooplankton</td>
</tr>
<tr>
<td>P4</td>
<td>Microheterotrophs</td>
<td>P5</td>
<td>Mucus Net Feeders</td>
</tr>
<tr>
<td>P6</td>
<td>Grazing Zooplankton</td>
<td>P7</td>
<td>Primary Carnivorous Zooplankton</td>
</tr>
<tr>
<td>P8</td>
<td>Secondary Carnivorous Zooplankton</td>
<td>P9</td>
<td>Ichthyoplankton, Type I</td>
</tr>
<tr>
<td>P10</td>
<td>Ichthyoplankton, Type II</td>
<td>P11</td>
<td>Carnivorous Merobenthoozooplankton</td>
</tr>
<tr>
<td>P12</td>
<td>Grazing Merobenthoozooplankton</td>
<td>P13</td>
<td>Plankton Eggs and Lecithotrophic Meroplankton</td>
</tr>
<tr>
<td>B1</td>
<td>Benthic Eggs</td>
<td>B2</td>
<td>Benthic Algae and Protophytes</td>
</tr>
<tr>
<td>B3</td>
<td>Photosynthetic Bacteria</td>
<td>B4</td>
<td>Microbenthos</td>
</tr>
<tr>
<td>B5</td>
<td>Melobenthos</td>
<td>B6</td>
<td>Infaunal Subsurface Deposit Feeding Macrobenhos</td>
</tr>
<tr>
<td>B7</td>
<td>Hard-Bodied Surface Deposit Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B8</td>
<td>Soft-Bodied Infaunal Surface Deposit Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B9</td>
<td>Soft-Bodied Epifaunal Surface Deposit Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B10</td>
<td>Soft-Bodied Infaunal Suspension Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B11</td>
<td>Hard-Bodied Infaunal Suspension Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B12</td>
<td>Epifaunal Suspension Feeding Macrobenhos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B13</td>
<td>Predators/Omnivores/Scavengers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Fecal Material</td>
<td>C2</td>
<td>Organic Aggregates</td>
</tr>
<tr>
<td>C3</td>
<td>Fine Particulate Organic Carbon</td>
<td>C4</td>
<td>Pelagic Dissolved Organic Carbon</td>
</tr>
<tr>
<td>C5</td>
<td>Benthic Surface Particulate Organic Carbon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>Benthic Subsurface Particulate Organic Carbon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Benthic Dissolved Organic Carbon</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

43 Compartments

Nekton Submodel (N) 10
N10, Penaeus spp. will be focal in impact analysis
3 species: Pink, White, Brown Shrimp

Plankton Submodel (P) 13

Benthos Submodel (B) 13

Organic Complex Submodel (C) 7
CARBON FLOW PROCESSES IN THE CONCEPTUAL GEM MODEL

12 Interior Processes
- Reproduction
- Uptake of DOM
- Ingestion
- Egestion
- Secretion
- Egg production
- Development
- Molting
- Mortality
- DOM production
- Physical agglomeration
- Physical breakage

5 Boundary Processes
- Migration
- Primary production
- Harvest
- Physical transport
- Respiration
Sector (Team) 1
Plankton 13

Sector (Team) 2
Nekton 10

Sector (Team) 3
Benthos 13

Sector Team 4)
Organic Complex 7

400+ binary transactions
### Controls

**Response** \( Y = R(Z, X, T, S, ...) \)

Temperature and Salinity were the main control variables formulated for the present brine disposal impact assessment.

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<table>
<thead>
<tr>
<th>Control factor</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>T</td>
</tr>
<tr>
<td>Salinity</td>
<td>S</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>O</td>
</tr>
<tr>
<td>Available nitrogen</td>
<td>N</td>
</tr>
<tr>
<td>Available phosphorus</td>
<td>P</td>
</tr>
<tr>
<td>Water depth</td>
<td>D</td>
</tr>
<tr>
<td>Sediment characteristics</td>
<td>M</td>
</tr>
<tr>
<td>Time of day</td>
<td>H</td>
</tr>
<tr>
<td>Light characteristics</td>
<td>L</td>
</tr>
<tr>
<td>Julian day</td>
<td>J</td>
</tr>
<tr>
<td>Fishing pressure</td>
<td>F</td>
</tr>
<tr>
<td>Estuarine discharge</td>
<td>E</td>
</tr>
<tr>
<td>Turbidity</td>
<td>C</td>
</tr>
<tr>
<td>Bioturbation</td>
<td>B</td>
</tr>
<tr>
<td>Physical resuspension</td>
<td>R</td>
</tr>
<tr>
<td>Waves, storm fronts, etc.</td>
<td>W</td>
</tr>
<tr>
<td>Intrusion</td>
<td>I</td>
</tr>
</tbody>
</table>

Table II.5.1. Factors controlling the carbon flow processes in the Gulf Ecosystem Model and their codes.

17 control factors
III. Brine Disposal Impact Assessment
The subsequent environ-based brine disposal impact assessment will focus on the Penaeid environs, which are only 2 of the $43 \times 2 = 86$ environs in the GEM model, each with the same potential:

... for specific attention

... and management mitigation & control
Percent deviations of selected model parameters to three perturbations from a reference salinity of \(~35 \,^\circ/oo\):

- 34 \,^\circ/oo
- 38 \,^\circ/oo
- 42 \,^\circ/oo

What the following GEM graphs will show...

1. Compartmental standing stocks

... and for the input and output environs of N10 Shrimp:

2. Intercompartmental C transfer rates

3. Compartmental C residence times

4. Compartmental C residence time variances
Except for some outliers, the compartments show progressive standing stock decreases with increasing hypersalinity.

Pelagic Planktivores (N1) and Organic Aggregates (C2) increase.

Conclusion
In general, the system loses biomass in proportion to the degree of hypersalinity.
BRINE IMPACT ASSESSMENT

% Change in Carbon Transfer Frequencies

With exceptions, the Shrimp I/O subsystem runs generally faster in proportion to the hypersalinity.

Input environ: % change in mean number of times C in shrimp (N10) has entered prior compartments

Output environ: % change in mean number of times C in shrimp (N10) will enter future compartments

30 and 33 of the 46 compartments show greatly increased C turnover in the respective input and output environs.

Conclusion
With exceptions, the Shrimp I/O subsystem runs generally faster in proportion to the hypersalinity.
Residence times decrease in 33 and 25 compartments in the input and output environs, respectively, in proportion to hypersalinity—but distribution patterns differ.

**BRINE IMPACT ASSESSMENT**

% Change in Residence Times

**Input environ:** % change in past residence times in days that C in N10 has resided in each prior compartment since entrance.

**Output environ:** % change in future residence times in days that C in N10 will reside in each subsequent compartment until exit.

Residence times decrease in 33 and 25 compartments in the input and output environs, respectively, in proportion to hypersalinity—but distribution patterns differ.

**Conclusion**

General reduction of C residence times reflects that the stressed Shrimp I/O subsystem runs proportionally faster under hypersalinity stress.
BRINE IMPACT ASSESSMENT

% Change in Residence Time Variances

Table IX.5

Output environ: % changes in future residence time variances

Except for the few outliers, most compartments in both environs show decreased variances in proportion to hypersalinity stress.

Input environ: % changes in past residence time variances

Conclusion

The Shrimp I/O subsystem exhibits narrowed responses in proportion to hypersalinity, reflecting stenotopic dynamics and systemic dystrophy.
IV. Implications for Ecosystem Health
Summary: Under hypersalinity perturbations, compartments and I/O environs exhibit proportional responses reflecting degree of sickness or wellness. Ecosystem illness is quantifiable by NEA. Where and to what degree.

- Compartments lose biomass
- Higher C turnover ⇒ I/O environs run faster
- Smaller C residence times ⇒ I/O environs run faster
- Smaller C residence time variances ⇒ I/O environs run narrower
Details differ, but the same kinds of results are evidenced by the other 42 compartments and 84 environs in the GEM model.

Malady is apportioned differentially to different ecosystem sectors enabling focused treatment of specific subsystems, species, and processes.

Network Environ Analysis (NEA) offers a promising model-based, whole-ecosystem methodology for comprehensive Environmental Impact Assessment and Ecosystem Health Assessment with high precision diagnostic, treatment, and management potential.

Because of its modeling complexities, demands for "big data", and lack of institutional markets capable of sustained commitment, it has never been tried.
1. In my career lifetime, in my field, there has been no mainstream market for IMM and related systems and modeling approaches. *Ecological modeling* remains a subfield, albeit robust, of the broader science.

2. Times are changing now, however, and there is urgent need for complex systems approaches to the complex systems of nature confronting humanity, beginning with the ability to organize disparate multidisciplinary and lay human resources into coherent wholes in themselves that can meaningfully address the essential wholeness of natural systems.

3. IMM is a complex systems protocol to create out of the minds of many a unified expert-systems vision that can carry over to and lead the development of technical complex systems approaches, particularly high-level modeling, and data and systems analyses (including *Environ Analysis*) that can serve as lenses through which to view and grapple with natural and human complexity.
4. **IMM** reached the proof-of concept stage 35 years ago, in a few projects I have described, and in particular the GEM model for the *Strategic Petroleum Reserve*. There has never been, then or since, a culture to embrace more, not in my field. Active resistance and rejection have been more the norm, prompting my (unpopular) characterization of ecology's "retreat into simplicity" following the 1970's *IBP Analysis of Ecosystems* program's reach-beyond-grasp demonstration of the incredible complexity in ecosystems.

5. A culture of holism, and institutional change to accommodate it, are needed now to move things along. This does not exist, but in my experience is a natural, even assured, outcome of theory-structured team-building in workshops and other collaborative settings.

6. Hopefully, this conference may prove a seminal event in moving things along.