June, 2019

System Designs for Integrated Models of the Gulf of Mexico

Contents

Background & Challenge

This memo documents the "MetaGoMRI" model, runnable at http://vensim.com/temp/gomri/

It is certainly worth exploring and critiquing the details of the model, so that we may improve it. At the same time, it may be best not to focus too much on the particulars of this model, because it is so preliminary. Instead, we propose the following strategic questions:

- What are the minimal requirements for detail and dynamics in each subsystem?
- What is the right level of simplicity needed to balance fidelity with transparency and defensibility in controversial public processes?
- What is the time horizon of greatest interest?
- How can we best exploit existing models and data?
- Where can we federate or chain components together, and where do we need tighter coupling to represent feedback?

On each point, one might ask, for what purpose, and for whom, are we modeling? Is there a niche for models that place oil spills in the context of climate change and coastal development, or does some other target offer higher leverage?

A Minimal Integrated Model

While it was beyond the scope of the 2019 project to create a runnable model, Ventana elected to do so, because it might generate useful thinking. Technically, we aimed for a model that would be:

- Simple, minimizing detail complexity in favor of scope and dynamics
- Broad, connecting physical and social effects
- Fast, for interactive exploration
- Transparent, with results traceable to assumptions and decisions
- Robust in extreme conditions
- Capable of embracing uncertainty
- Calibrated to data (on this front we made little progress due to time limitations – much more could be done)

In addition, we felt that the model should include a few key, qualitative features of the GoM system that emerged during elicitation of the CLDs:

- One or a few state variables for each of the 4 boxes.
- At least one major link between each pair of boxes, especially in the underrepresented health and socioeconomic domains.
- A tradeoff between mitigating oil surfacing with dispersants and toxicity.
- Irreversibilities in ecosystem-habitat interactions, such that permanent damage might occur.
- Tension in coastal economies between losses from closures and gains from cleanup activity.
- Delayed health effects.
- A closed loop between socioeconomics (the community-economy) and health, through mental health impacts and productivity.

At a high level, the feedback among subsystems is shown in Figure 1.

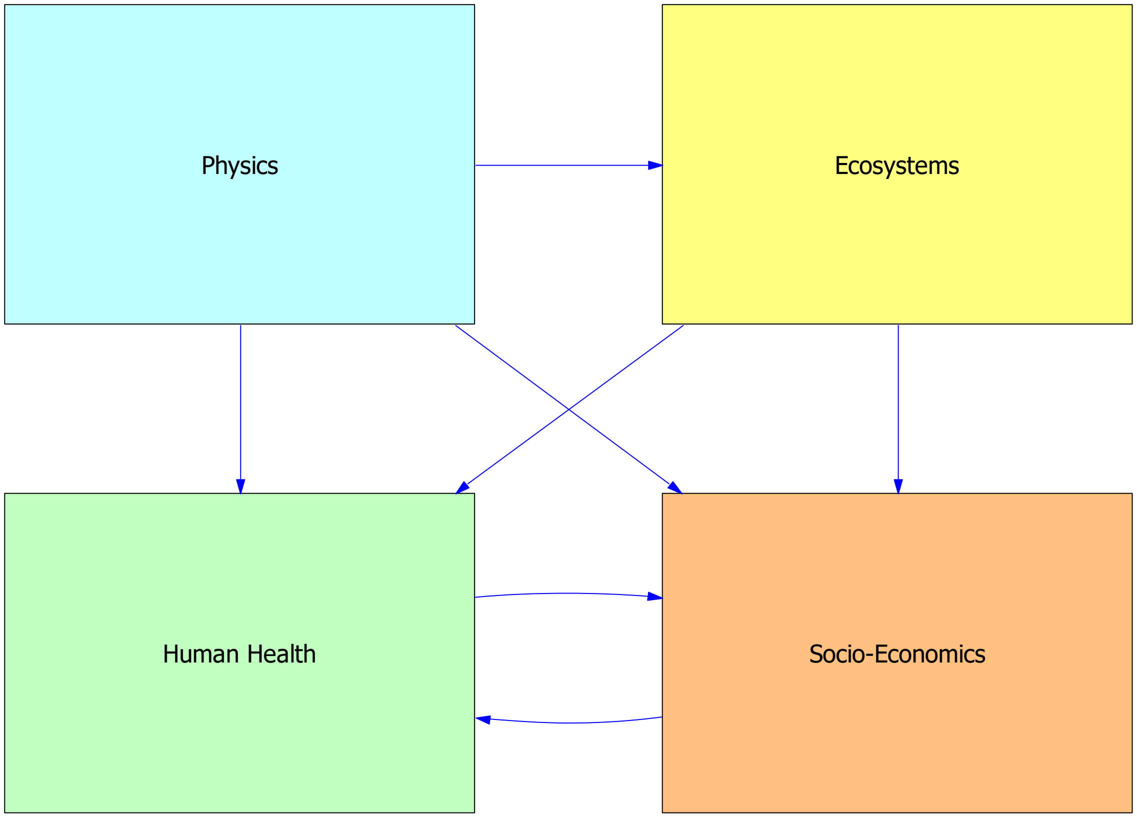

Figure 1: High level feedback among subsystems in the Meta-GoMRI model.

The model is implemented in Vensim using System Dynamics methodology. That is to say, it is a system of ODEs representing physical variables as well as behavioral decision making. It is extremely simple overall, with 11 state variables and just over 150 equations and parameters in total. It runs on an abstract 20-year time horizon, and is notionally parameterized to resemble the Deepwater Horizon spill in scale. Most variables are indexed in relative or arbitrary terms rather than calibrated to actual GoM values.

Physics

The physics sector contains an aggregate ocean with dispersion of toxins via diffusion processes with first-order dynamics at each point (Figure 2). It is driven by exogenous release of oil (at bottom). It has no inputs from other sectors, and therefore ecosystem dynamics influencing oil transport are not captured, for example. Three policies are available: surface oil cleanup (e.g., skimming), deployment of booms to slow transport of oil onshore, and cleanup of beached oil. Each of these creates a negative feedback loop at the top of the diagram.

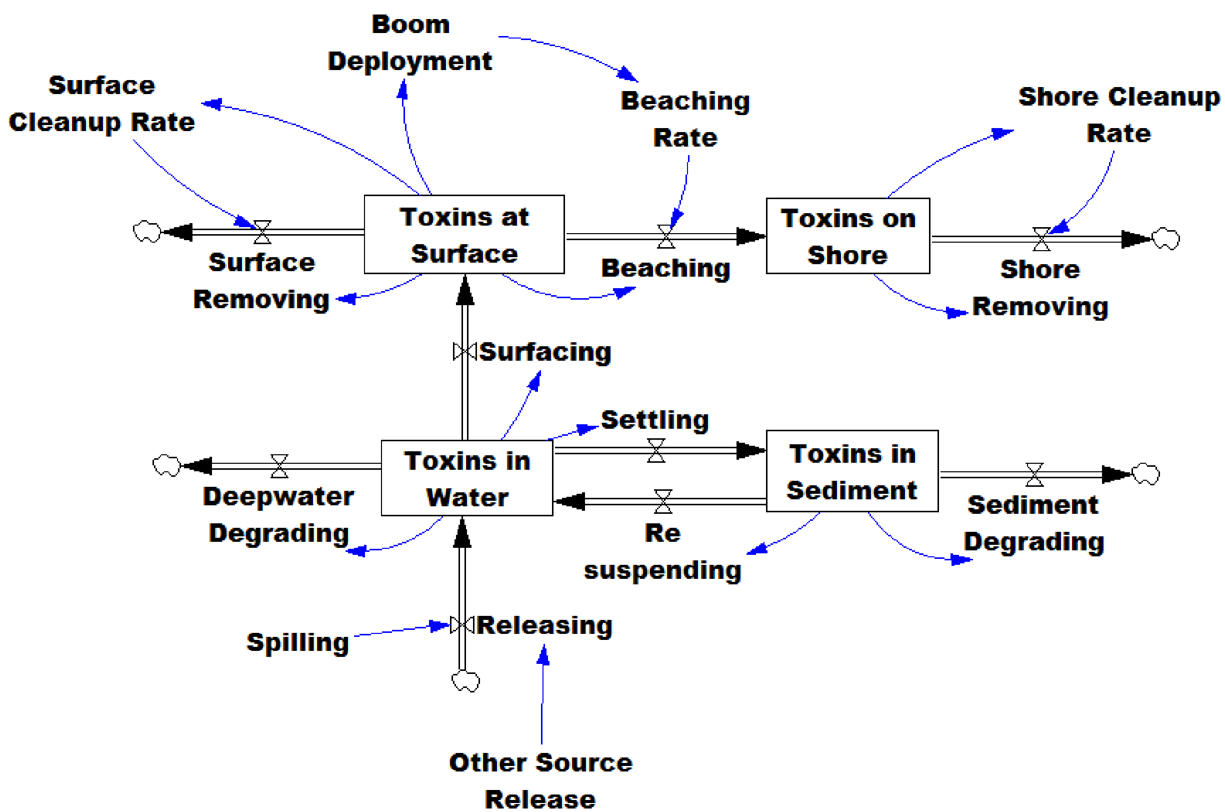

Figure 2: Physics subsystem.

Each policy is represented by an extremely simple behavioral decision rule. For example, boom deployment is a nonlinear function of the observed presence of toxins (i.e. oil) on the surface (Figure 3). While in reality there would be implementation delays and constraints on deployment due to the availability of equipment, these are neglected. The thresholds for action on each policy implicitly reflect economic and health considerations from other sectors.

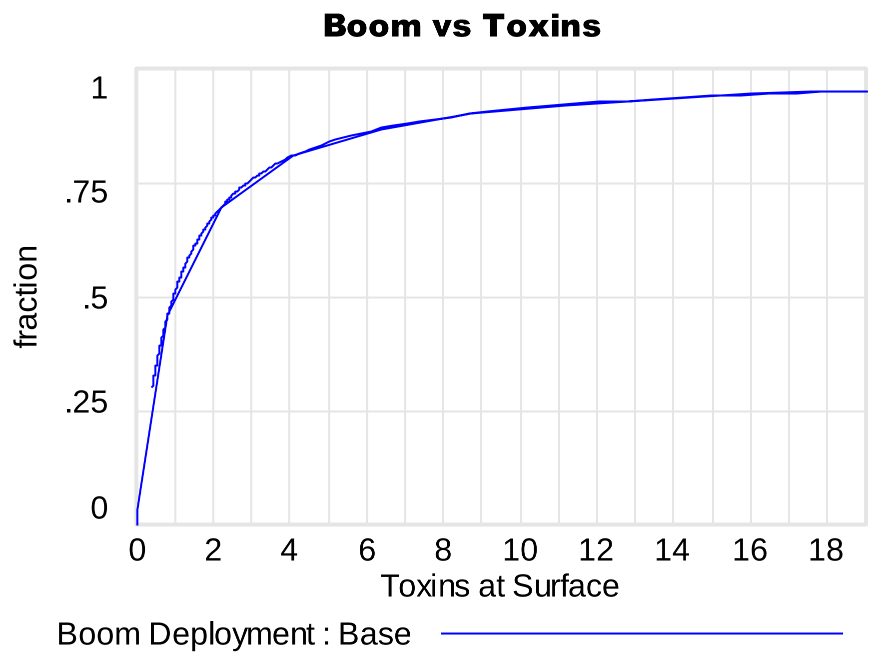

Figure 3: Boom Deployment as a function of Toxins in Surface Water.

Ecosystems

The ecosystem sector contains two states: biomass and habitat. Biomass health is influenced by mortality from toxicity, which is a weighted average of the presence of toxins (i.e. oil and dispersants) in the 4 states of the physics sector. Habitat is influenced by disturbance from shore cleanup, e.g., adverse sedimentation from excavations. The stable habitat depends on the quantity of biomass (as, for example, shorelines depend on seagrass for stability) and in turn the biomass carrying capacity depends on the extent of habitat (as fish require healthy reefs).

Aggregation of the ecosystem into two states is obviously heroic to the point of absurdity, but the structure does represent a few important features of the real system. Because it is nonlinear and path dependent, a temporary disturbance can have a sustained negative impact on biomass and habitat (Figure 5).

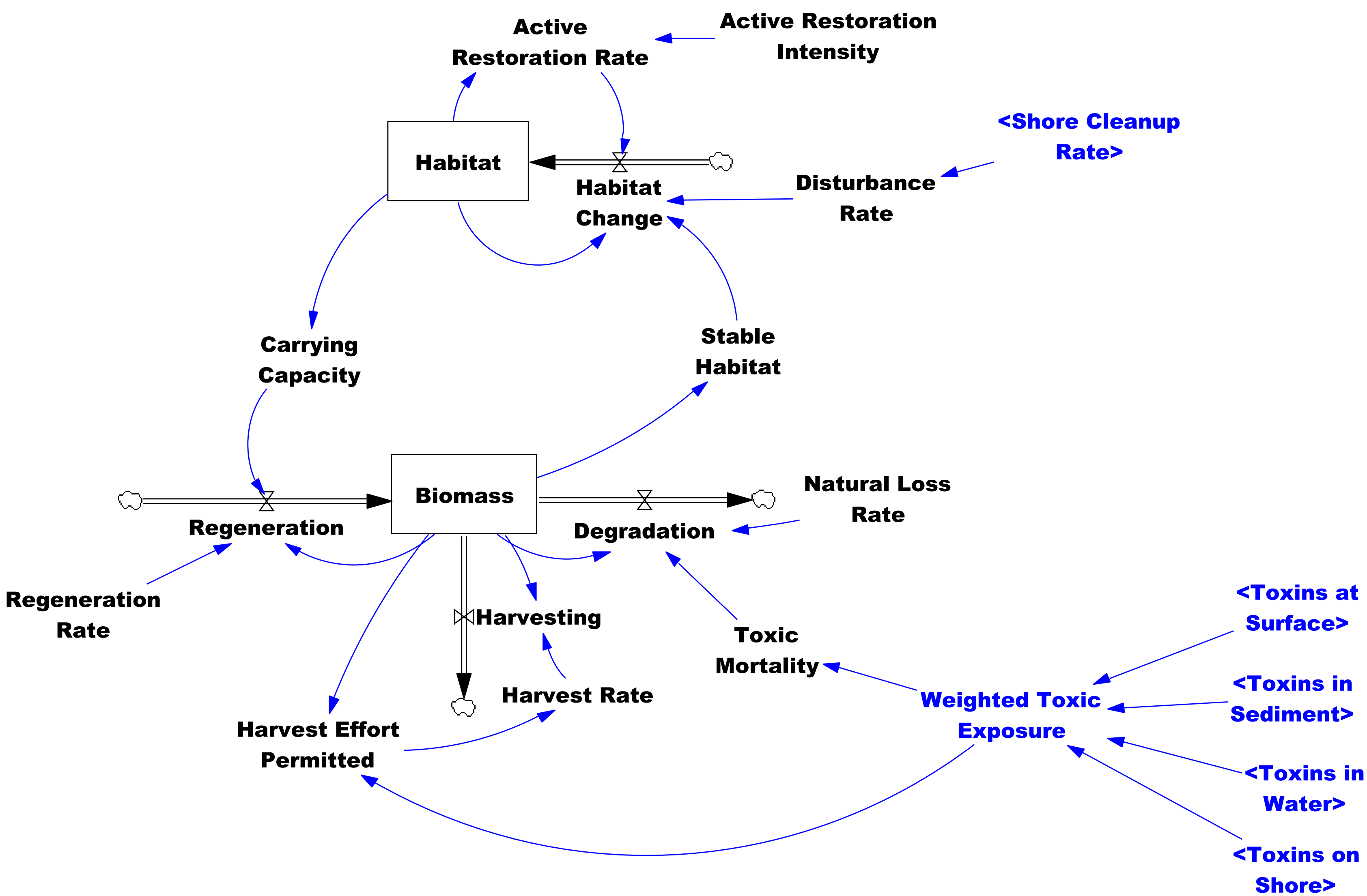

Figure 4: Ecosystem sector, with biomass and habitat states. Blue variables indicate inputs from the physics sector.

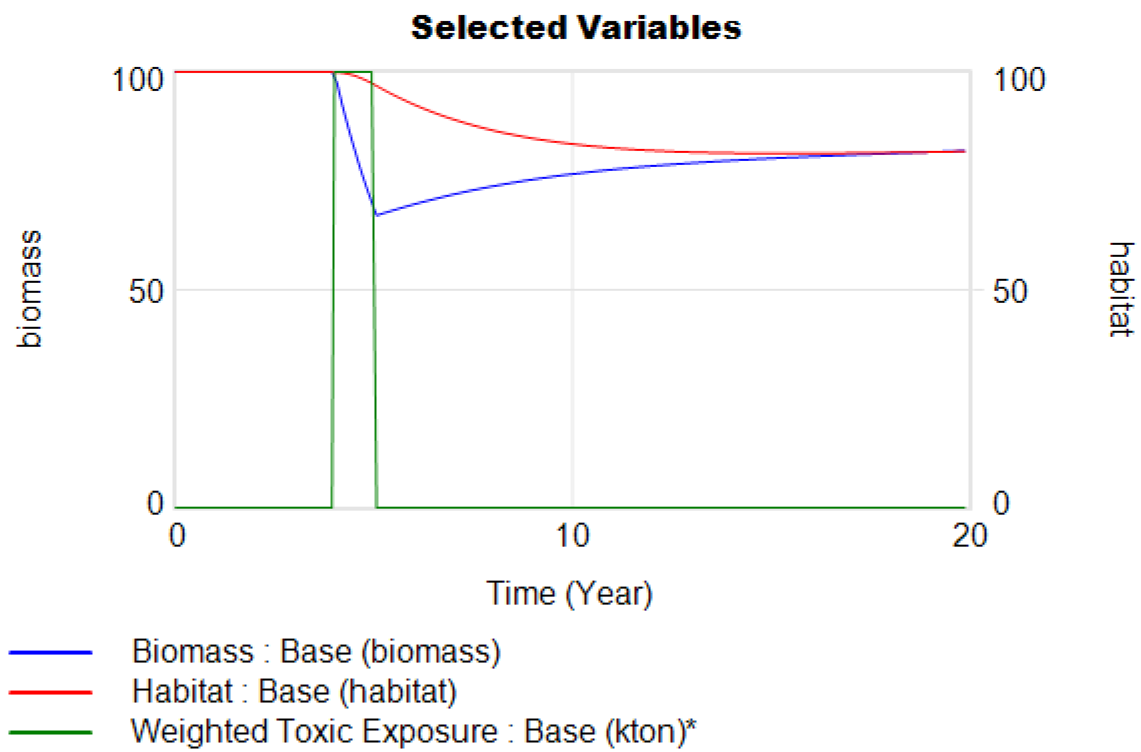

Figure 5: Biomass-habitat response to a temporary toxic event. Green: an externally-imposed toxic event with duration of one year. Blue: toxicity immediately reduces biomass via mortality. Red: reduced biomass leads to erosion of habitat, and therefore diminished biomass carrying capacity, preventing the system from returning to its original state.

Two policies are possible: active restoration of habitat, and biomass harvest. Harvest takes a "normal" fractional rate of biomass, unless the presence of toxins above a user-specified threshold indicates that fishing should be diminished. As for boom deployment, this is a continuous, nonlinear function rather than a binary decision, reflecting the fact that many regions facing different exposures are aggregated. Restoration is a user decision, and is costly.

Human Health

This sector captures effects of exposure to oil and its economic side-effects on human health. There are immediate, acute health effects driven exposure to toxins, as well as delayed chronic effects. Each is driven by a dose-response curve that could be (but has not been) parameterized to data or more detailed models. Mental health is represented by a first-order model with simple regeneration and degeneration processes, driven by stress from health and economic factors. Poor mental health is also a contributor to poor physical health. Like the ecosystem model, the health model can have a tipping point such that excessive toxic exposure or economic hardship can drive the system into a degraded state, from which it is difficult to return.

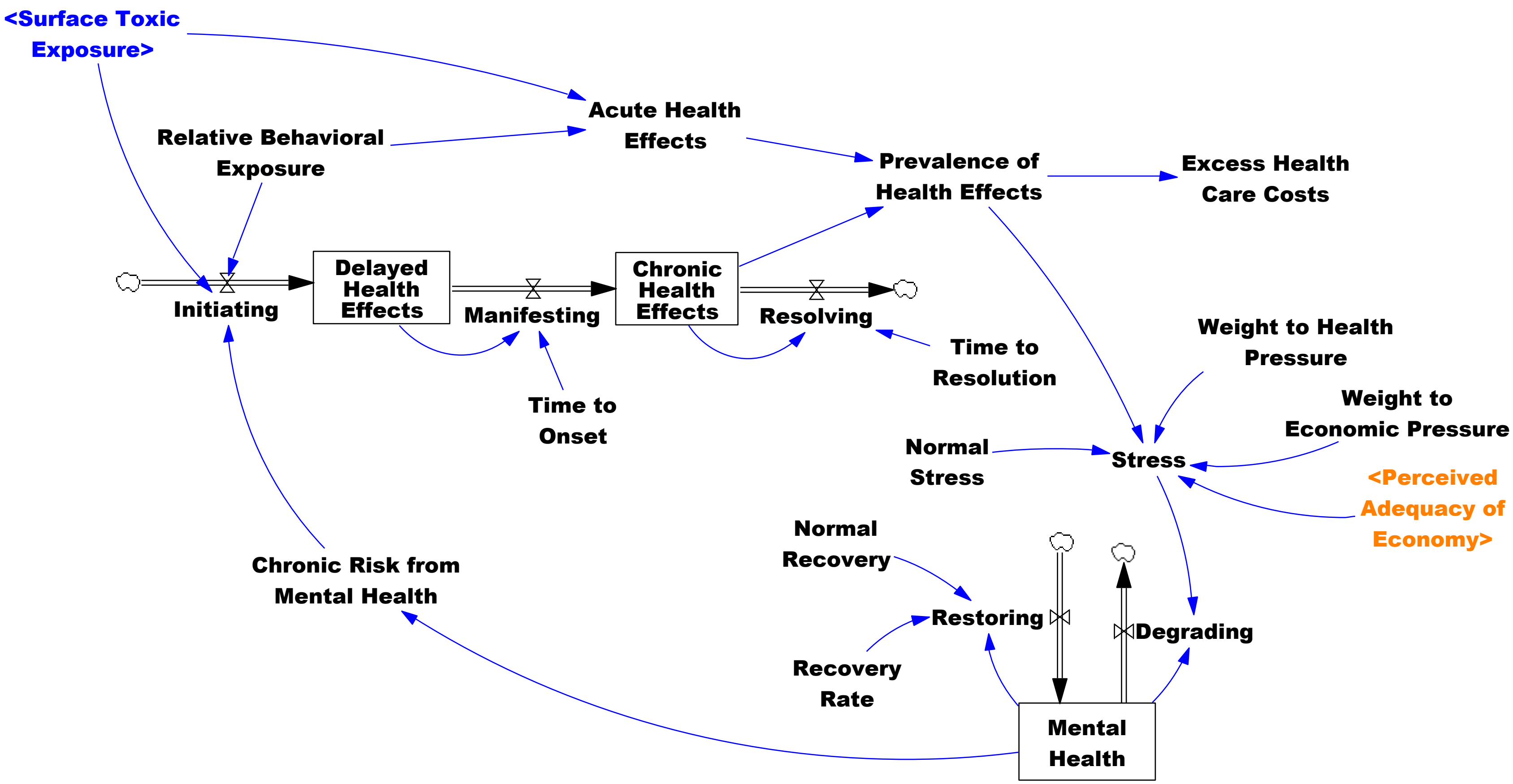

Figure 6: Health sector. Blue: toxic exposure from physics sector. Orange: mental health exposure to economic impacts in the socioeconomic sector.

Socioeconomics

The socioeconomic sector primarily captures activity in coastal economies. Economic activity is a function of cleanup expenditures, the value of ecosystem harvesting, and tourism. A multiplier captures spillovers to other sectors. Productivity is also important; it is influenced by mental and physical health as well as human capital build through educational investments. This creates another possible tipping point dynamic: if diminished activity or excessive health care costs make education unaffordable, diminished human capital will reduce long term productivity, and therefore value, creating a kind of poverty trap.

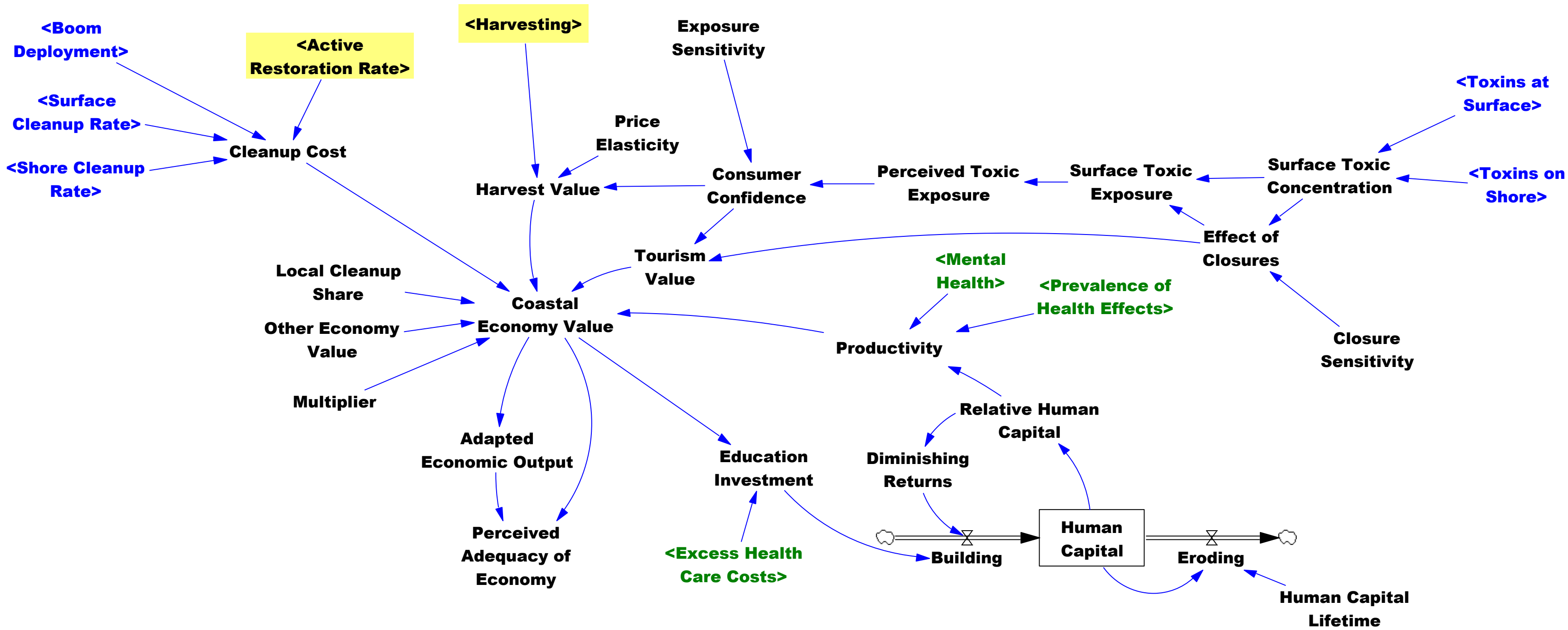

Figure 7: Socioeconomic sector. Blue: cleanup costs and toxin drivers of fishing and tourism closures from the physics sector. Yellow: biomass harvest and habitat restoration costs from the ecosystem sector. Green: health care costs and productivity effects from the health sector.

Stakeholder Perspectives

A simple control panel permits experimentation with the model and review of results from multiple perspectives. Figure 8 and Figure 9 illustrate application to three simple scenarios. The blue and red scenarios are spills without any response. In the blue scenario (labeled NoFeedback), feedbacks between health and the community-economy are inactive. The economy does not influence mental health, and health does not affect productivity. In this case, the harm to the coastal economy from the spill is modest, primarily because productivity remains constant. In the red scenario (labeled Base), these feedbacks are active. The community-economy-health feedbacks amplify the modest direct impacts of the spill, leading to severe economic and health effects. The economic harm to communities is further amplified by budget constraints, as spending is diverted from productive investments in human capital, degrading future productivity.

In the green scenario, use of dispersants increases the toxicity of oil, but reduces transport to the surface and shore. Cleanup efforts and booming further reduce the transport of toxins into the most sensitive environments. As a result, biomass and habitat damage and health effects are dramatically reduced. The tradeoff for these benefits is large cleanup costs (Figure 9, bottom right panel).

Uncertainty

Since little effort has been devoted to this model to date, its results are at best highly uncertain. But even if it were extensively calibrated and validated, much residual uncertainty would remain. Figure 10 illustrates an approach to uncertainty via Monte Carlo simulation, with a few key parameters draw from (arbitrary) probability distributions. In a fully developed model, a similar approach could be used to give stakeholders an appreciation for the uncertainty in tradeoffs and decisions, and to seek policies that would perform robustly in the face of unkowns.

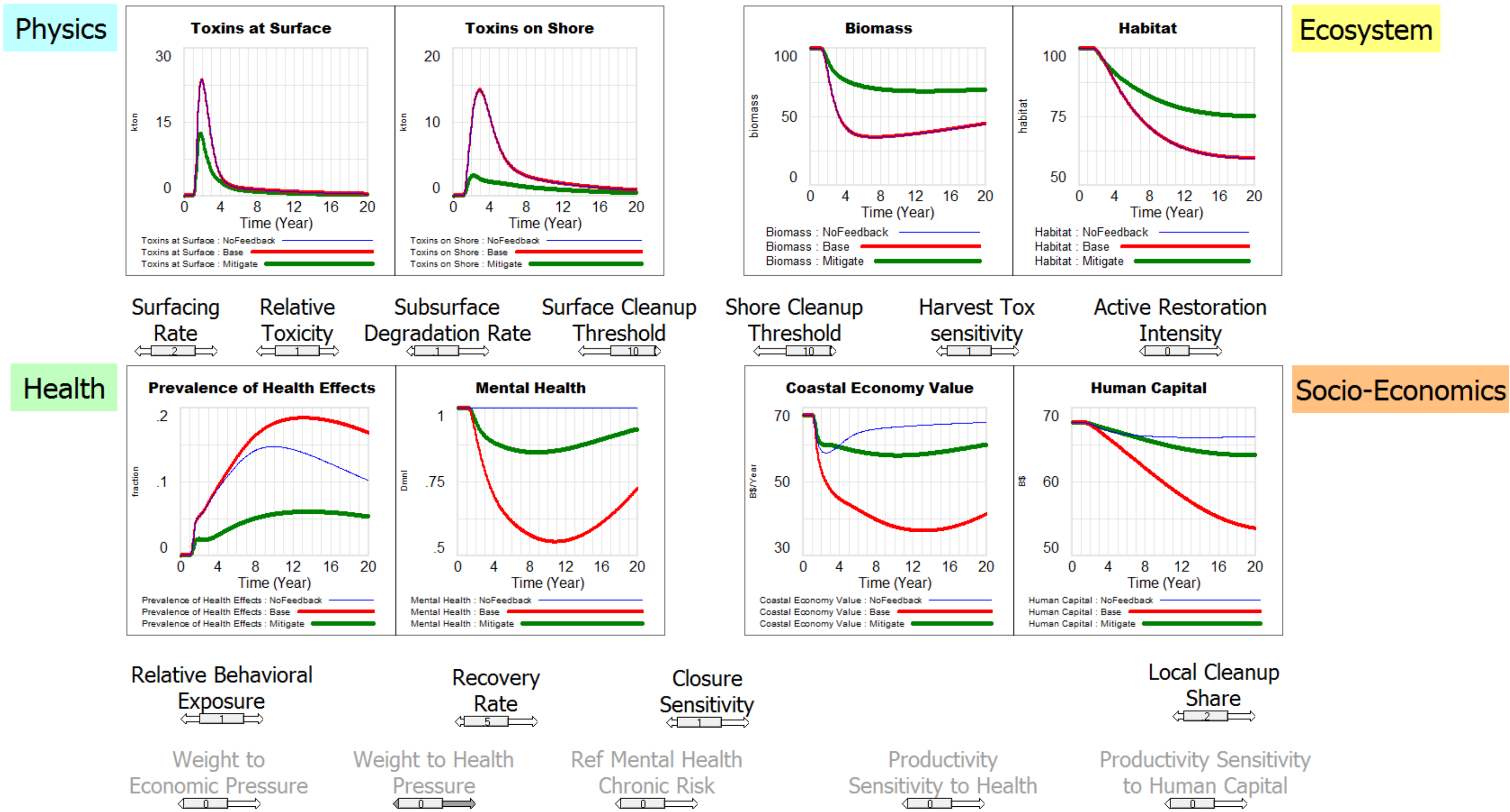

Figure 8: System states control panel.

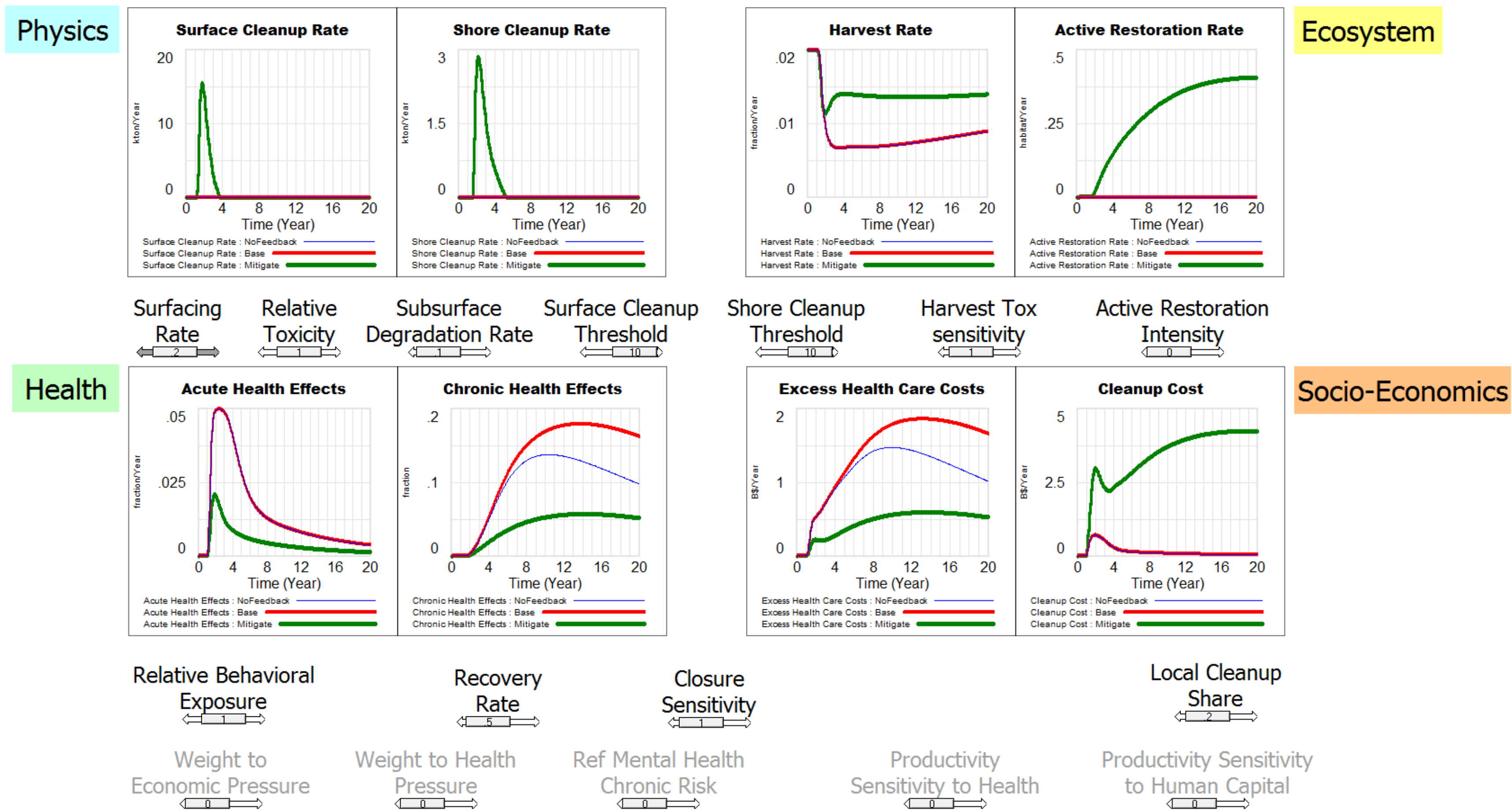

Figure 9: System rates control panel.

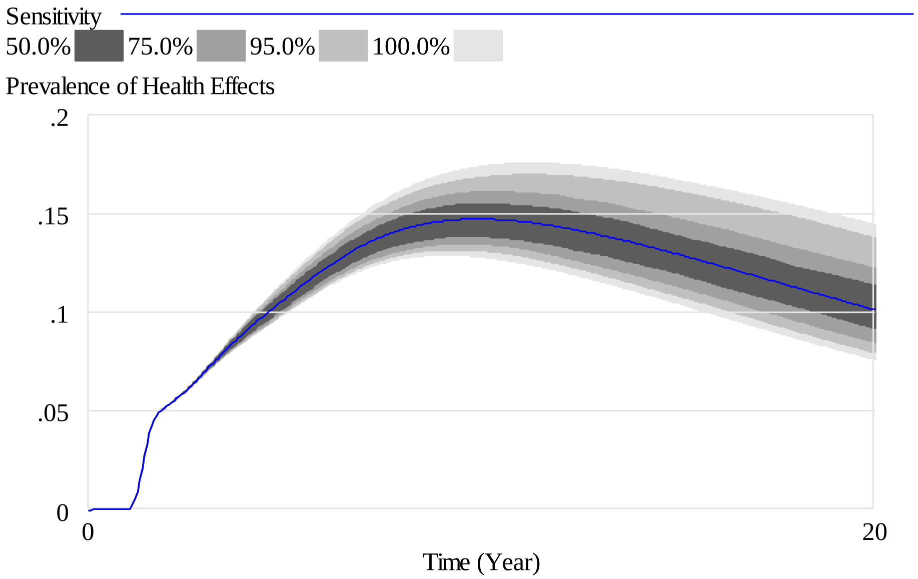

Figure 10: A sensitivity simulation, showing confidence bounds for health effects.

Extensions

This minimal metamodel would support an approach complementary to federation of detailed domain models. The top-down approach would support analysis of new kinds of long term strategic questions, such as determining the optimal level of effort devoted to spill avoidance. It would also permit the development of linkages to broader domains of great importance to the future of the Gulf, such as coastal development and climate change.

An enhanced top-down framework could also be the basis for a reusable component architecture. A researcher could replace one or more aggregate components with detailed models for a particular purpose, preserving the contextual value of the aggregate components with little additional work. The top-down model cannot exist without bottom-up, detailed research, which it needs for validation of its operational description of reality. Together, the two approaches could support a variety of new questions for models, adding value to existing research and improving quality of life in the Gulf.