A Conceptual Model for Environmental Monitoring of a Marine System Developed for the Puget Sound Ambient Monitoring Program

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Introduction

Environmental monitoring programs are established to assess the status of ecosystem components with the goal that this information will be used to direct human management decisions. The Puget Sound Ambient Monitoring Program (PSAMP), established in 1988, is a multi-agency monitoring program focused on assessing the health of and protecting the Puget Sound Ecosystem (PSWQA, 1996). In 1995, the first comprehensive review of PSAMP was conducted by an external review panel of nationally regarded scientists (PSWQA, 1995). A major result of the review, as related in "Panel Findings and Recommendations" (Shen, 1995), was that PSAMP lacked a "big-picture" focus and was not well integrated. To promote these attributes, the review panel recommended that PSAMP develop a conceptual model that incorporates stressors, key processes, and both ecosystem and management linkages. They asserted that this approach promotes integration of all monitoring efforts and linkage of goals/questions and technical elements of the monitoring design to management needs. The PSAMP Steering Committee, in unanimous agreement with the panel recommendation, responded by establishing a working group to address the formulation of a conceptual model for Puget Sound. In this document we: 1) detail the product of this effort, a matrix from which conceptual sub-models can be drawn; and 2) describe how these products can be used to promote program integration and better linkage with management.

Key aspects defined at the outset for the modeling effort were that it would allow a visual representation of our best understanding of the key components and functions in Puget Sound and human effects on it. The model would identify three levels of relationships: natural processes (e.g., trophic processes, energy transfer, physical relationships); stressors and anthropogenic perturbations (e.g., point and non-point source pollution, harvest, freshwater diversion, marinas); and human management and policy practices (e.g., agencies involved in regulation, criteria levels, management practices, public actions). The model would identify and define linkages within, as well as among, these three levels of relationships.

The model is a communication tool, designed to show where information gaps are, where effort is being placed, and who or what efforts are involved on a particular ecosystem issue. The model is dynamic in time. We envision that the model will be used to define monitoring efforts and, in turn, the results from monitoring and research from within Puget Sound will be used to refine the model. Use can be viewed in a feedback loop as follows:

1. Provide general scientific agreement for the ecological framework of Puget Sound;
2. Provide a basis to identify gaps in knowledge and understanding;
3. Provide a basis for managers to ask questions, to see the complexity of the information required for answers, and to see relationships between management activities and ecosystem response;
4. Provide a basis for scientists to design monitoring and research programs to answer questions; and
5. Provide context for presenting results.

A feedback loop is established based on using #5 to reinterpret #1 and #2 and then to reassess #3 and #4. Thus, in summary, the fundamental roles of the conceptual model are to:

- Identify and unify the various areas of attention being addressed by PSAMP investigators into specific topics;
- Provide a communication tool, particularly so that one may view the effort of all (not just PSAMP) entities with concerns and/or assessment efforts;
- Explicitly identify linkages within as well as between anthropogenic activities, human management policies, and ecosystem components; and
- Explicitly identify gaps where more effort or awareness should be applied.

Approach

Numerous examples of ecosystem-level conceptual models were identified (Proctor et al., 1980; NOAA, 1983; Clark, 1986; Galveston Bay NEP, 1994). While format and complexity vary substantially, one pattern was that several models are typically needed to describe a system or a program. The models are tailored to serve the messages that each program is making or the audience that is targeted. In such models, there are several categories of information that provide input data for the conceptual model. Several of the categories are represented in Figure 1, which shows the relations between these pools of information. We identified four categories that we wanted represented in our conceptual model that would help us define our monitoring program: Human Activities, Stressors, Ecosystem Components, and Management. Figure 1 also shows how these categories relate to Society and Monitoring programs. Because of the complexity of the information within each category and the variety of linkages, we felt the information could best be handled by placing it in a multi-level matrix. The matrix serves to store, organize and link all input information from each of the categories. The matrix can then be used as a reference tool for construction of visual models. This matrix will be published in a more comprehensive documentation and description of the conceptual model.

The information and linkages portrayed by our visual "conceptual sub-models" are those which were distilled from the matrix. Presentation via the conceptual sub-models is in a more visually informative format and the format can be adjusted to contain more or less detail, as desired, for various audiences.

Matrix Description

Four categories of information have direct bearing on the health of Puget Sound. Each category forms an axis in a linked matrix. The categories are:

1. Components: Components of the greater Puget Sound system are divided into Ecosystem Health and Human Health. Ecosystem health is broken down into the physical, chemical, and biological components of each environment (nearshore, bays and inlets, and open basin). Human health is broken into areas where contact and consumption may be hazardous.

2. Activities: These are activities that impact the Puget Sound environment. Largely these are human actions, but also include natural mechanisms of change within the system. We distinguish construction vs. operation activities, on/over water/shoreline vs. upland activities, and marine vs. freshwater activities. We also distinguish the activity from the resulting stressor(s).
3. Stressors: These are stressors caused by or resulting from the activities described. This category typically contains verb-noun combinations, e.g., "change sediment type" or "increase nutrients."
4. Management: These are governmental regulatory and proprietary programs that have bearing or relevance on the activities listed.

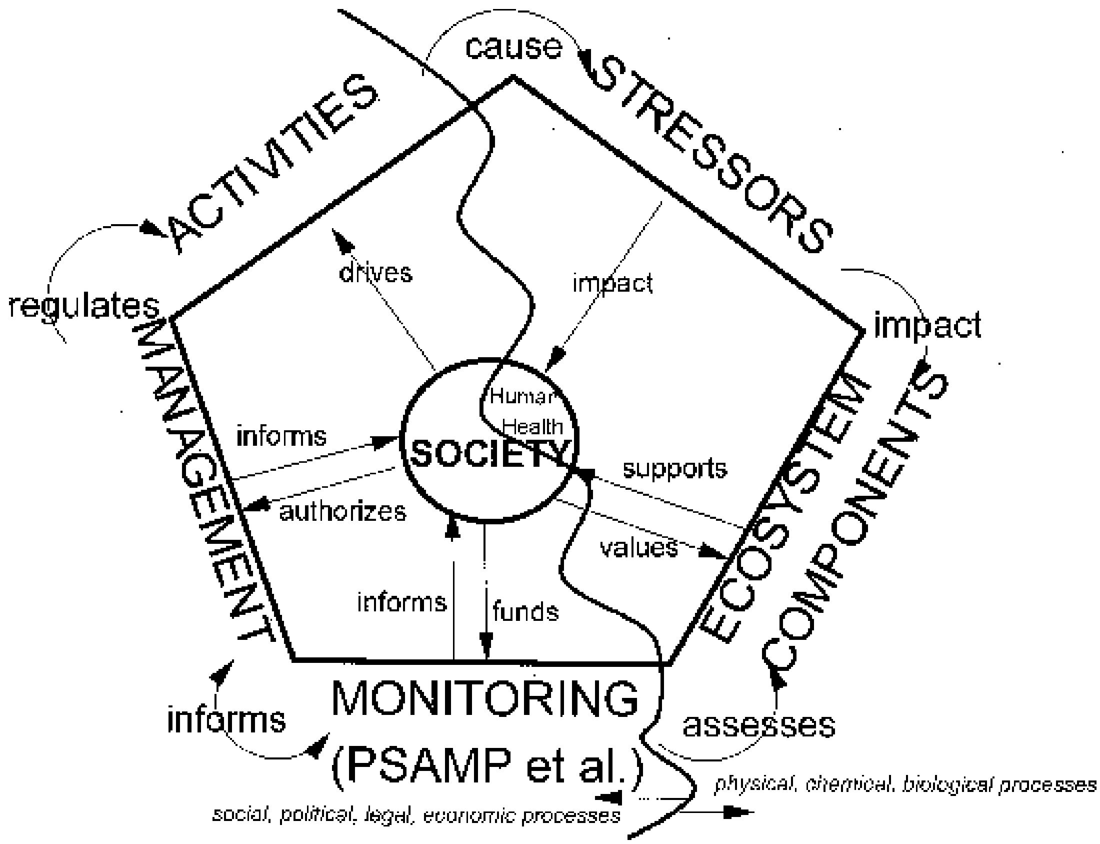

Figure 1. Conceptual model of the relations between key categories involved in environmental monitoring and assessment.

The matrix is primarily described by three associations: activities with management (via regulation); activities with stressors (via causation); stressors with components (via impact). A representation of the relational setup for the matrix is shown in Figure 2. The full matrix and its glossary is currently being printed and will be available in a separate document published by the Puget Sound Water Quality Action Team.

To assess human impacts on the Puget Sound ecosystem, one may first consider the human activities; we have then identified the **stressors** caused by these activities (matrix A), and the management that regulates the activities (matrix B). It must be noted that since both natural and anthropogenic **activities** can cause the same stress, in some cases the human impact alone cannot be assessed unequivocally. In addition, a smaller matrix (matrix C) has been added because although we are treating Puget Sound as a closed system, it is not. There are external natural inputs to the system that may modify the impact of stressors in a negative or positive way that must also be considered. Stressors are then followed across to identify which of the **components** of the ecosystem or related human health that they impact (matrix D). A glossary to define the terms in all the categories of the matrix follows this document.

At the intersections of the columns and rows in matrices A, B, and C, a check mark appears if there is an association between the two items. Question marks are used in a few cases where the linkage may or may not occur. At the intersections of the headings in matrix D, association is indicated in various ways by use of several symbols. We differentiated direct from indirect associations based on whether the stressor acted directly on that component (e.g., added toxics kill benthic fish) or acted through an intermediary component (e.g., added nutrients change primary production, which affects fish), which we termed indirect.

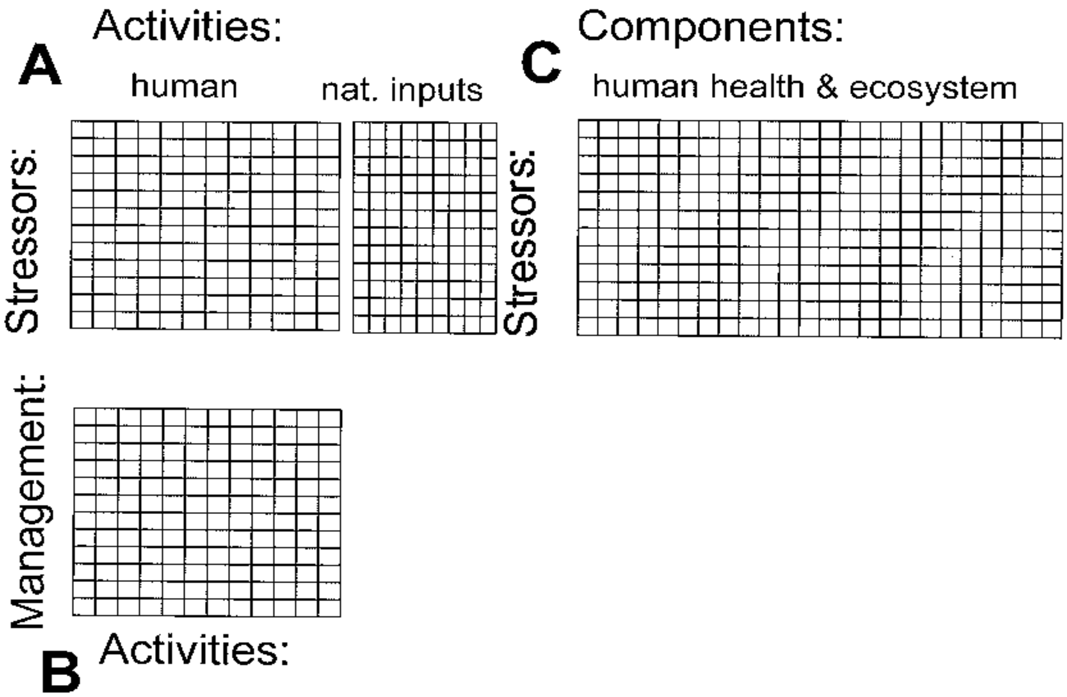

Figure 2. Organizational relations between categories, shown as axes of matrices, used to organize key environmental monitoring.

We divided the Puget Sound natural ecosystem into three non-overlapping areas: nearshore, bay/inlet, and open basin. "Nearshore" is taken to be a region marked by its elevation or depth relative to sea level based on habitat attributes (highest extent of seawater plants to depth of benthic euphotic zone). In this usage, the "bay/inlet" and "open basin" areas both exclude this nearshore portion. These latter two areas differ in their degree of physical enclosure: "bay/inlet" represents the portions of Puget Sound that are ringed by shorelines, somewhat protected, and typically shallower (e.g., Commencement Bay, Sinclair Inlet); whereas, "open basin" represents the deep, typically well mixed basins (e.g., Main Basin, Whidbey Basin). However, no categorization is perfect; places such as Hood Canal have areas with attributes of both bay/inlet and open basin. The purpose of having three areas is to evaluate which impacts change and which stay consistent regardless of physical characteristics.

In summary, the matrix associates various activities with components of Puget Sound ecosystem and human health. We have done this by explicitly identifying which stressors and what management are associated with each activity as well as how resulting stressors are translated to the various aspects of the ecosystem. These features directly satisfy the key aspects desired for the PSAMP conceptual model, as stated at the outset of this effort.

With this much inherent detail and complexity, modeling the entire system represented in the matrix would likely prove unyielding. However, as described below, the matrix can be used to construct more manageable conceptual sub-models that represent a portion of the entire system, focusing on one stress or one component and identifying all of its linkages. Not only can the matrix be used to construct conceptual (sub)-models, but PSAMP investigators also have used it to identify monitoring topics, integrated questions, and to point to possible environmental indicators.

Matrix Limitations

There are several limitations to the matrix that bear mention before demonstrating its use to create conceptual sub-models. First, no "currency" or specific parameterization (e.g., abundance, carbon, or health) has been defined for the ecosystem component categories. Although the matrix identifies linkages between stressors and ecosystem components as impacts, the nature of the impact is undefined. For instance, a stressor can impact an ecosystem component through a reduction in number/concentration, through substitution or loss of species, through change in individual health, etc. We identified an impact when any type of alteration could be identified. Thus, when constructing models, it cannot be specified from the matrix *a priori* whether the model tracks carbon flow or species impacts. This must be decided by the user, taking into account the underlying mechanisms by which stressors act on components and the responses of the components to stressors.

A second limitation is that when indirect associations are shown, the nature of the indirect association has not been defined in the matrix. A more complete model of the system would indicate relationships between ecosystem components. The user must employ knowledge of ecology and incorporate aspects of ecosystem function into sub-models.

A third limitation is the overlap in and the subjective nature of the three physical ecosystem areas we have defined. We have already acknowledged the difficulty of fitting all Puget Sound areas into one of these three. There are further considerations that must be taken when modeling. While the physical differences in the three areas are appropriate on the scale of vegetation and plankton, many macrobiota (e.g., lingcod, rockfish, grebes) freely swim or fly between areas and may spend time equally or randomly between all three. Thus, when constructing a model for these organisms, one must consider all associations noted and make a sub-model that combines them to a suitable degree for the organism or population. Due to scaling and dilution factors, in most all cases impacts on organisms are worst in the nearshore, followed by bay/inlet, followed by open basin.

Use of the Matrix to Develop Conceptual Sub-Models

Conceptual sub-models are basically a visual representation of the linkages associated with a specified portion of the matrix. This can take any format but both stressor-based and component-based models have particular utility for planning environmental monitoring. Construction of a conceptual sub-model consists of taking a particular heading in the matrix and linking all the headings connected to it. An example of this is shown in Figures 3 and 4, which are stressor-based and component-based models, respectively.

To produce a more integrated and defined monitoring program, within PSAMP the principal investigators evaluated the list of stressors in the matrix and chose the topics shown in Table 1 that would focus on the listed stressors. Examples of conceptual sub-models that illustrate topics are shown in Figures 5 and 6.

Benefits of the Approach

One utility of the modeling exercise is in aligning the monitoring framework and emphases with the conceptual sub-model, such that gaps are identified. For instance, for the Human Health topic, there are no identified activities or stressors driving the causes of biotoxins. This is a research need. For both the Toxics and Nutrient topics, we have used the model to identify areas where monitoring should be focused. To address these areas, are scoping pilot projects in focused areas: toxics in the lower levels of the food chain (e.g., plankton); and nutrient effects on vascular plants, respectively.

The PSAMP conceptual models are now being used as tools to communicate with management regarding program focus and related policy attributes, with the public regarding the emphasis of PSAMP relative to the entire system, and with other scientists, particularly colleagues involved in similar or related programs and interests in order to forge a better understanding of the environmental status, as well as to form new collaborations.

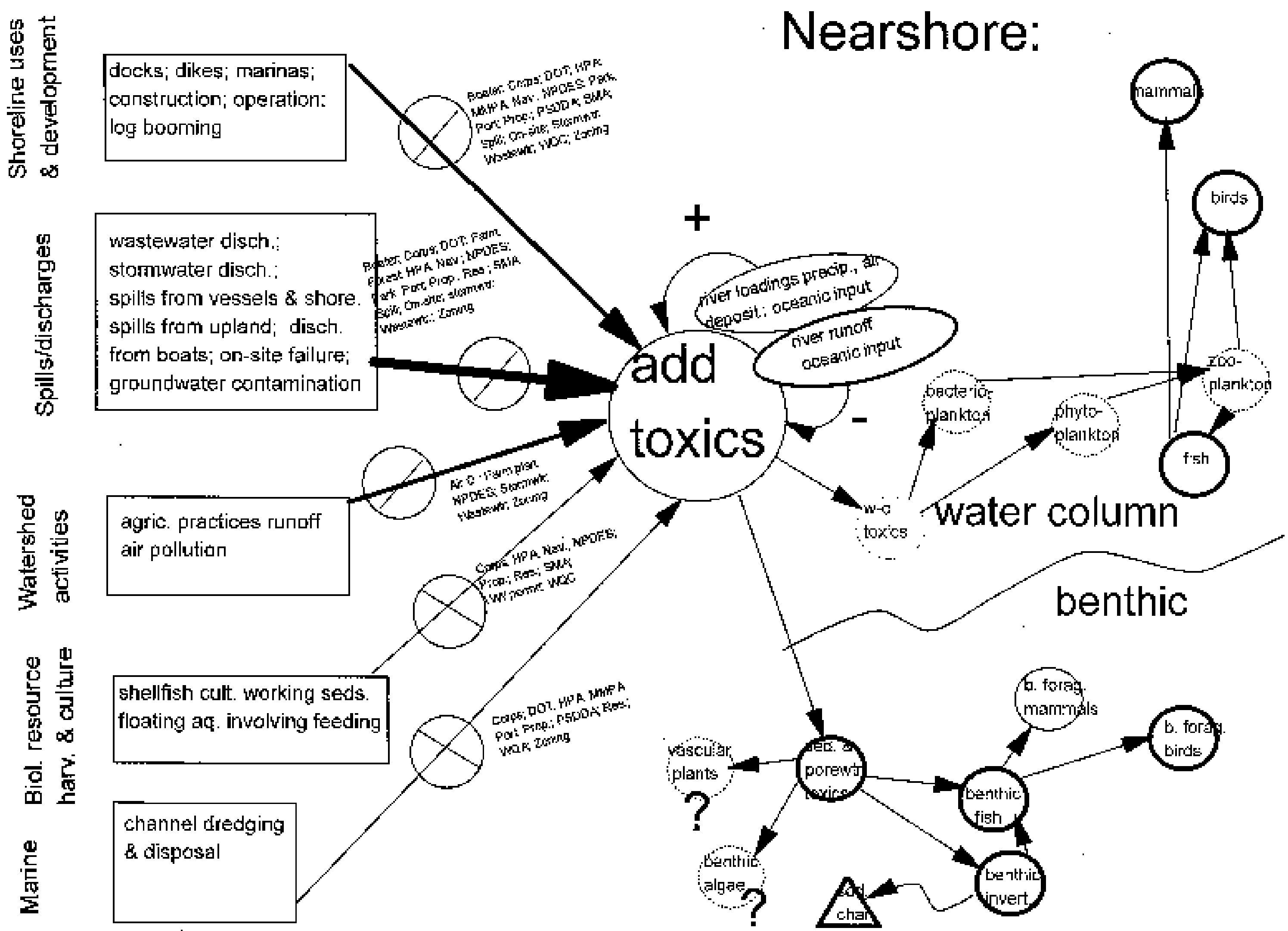

Figure 3. Stressor-based conceptual sub-model for toxics in the nearshore environment. Weighting of line around ecosystem component circles indicates amount of monitoring data available.

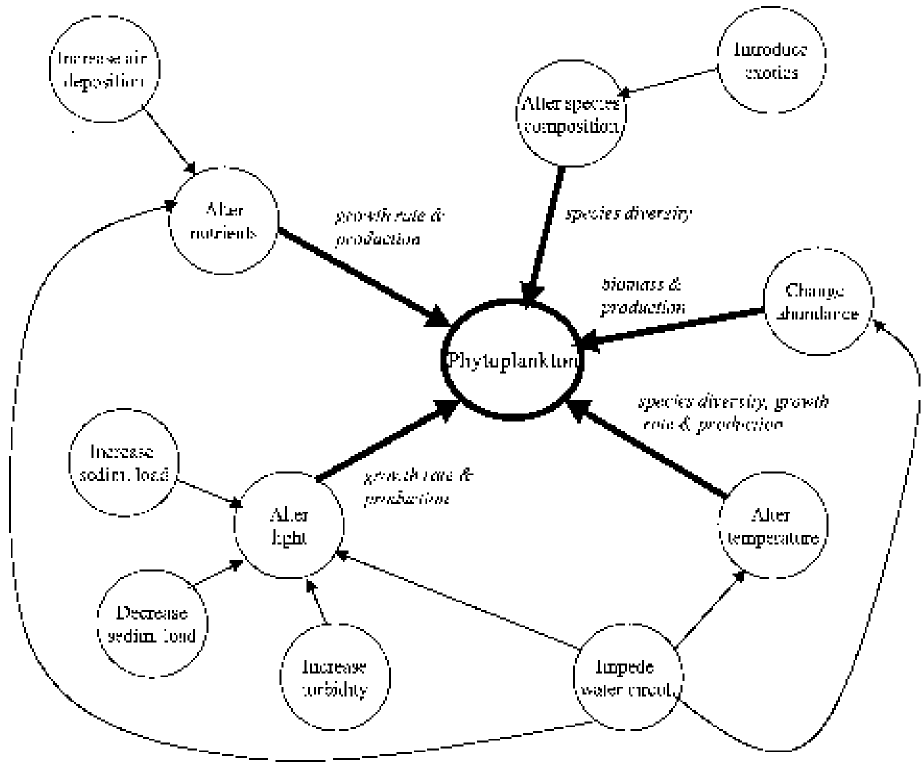

Figure 4a. Component-based conceptual sub-model for phytoplankton. The phytoplankton attributes that are affected by the stressors are shown in italics.

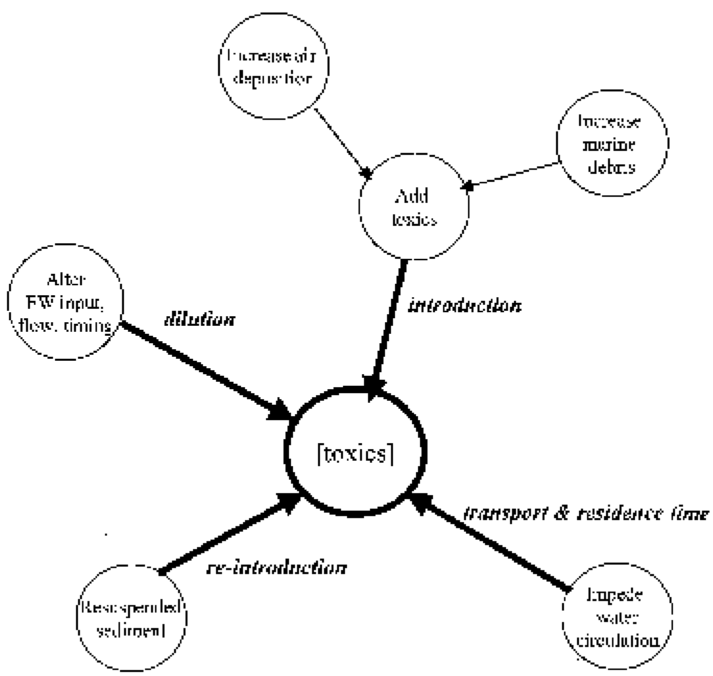

Figure 4b. Component-based conceptual sub-model toxics concentration. The mechanism for the effect is shown in italics.

Table 1. Stressors categorized into topics showing where present PSAMP monitoring effort is currently applied. A sixth topic, "Human Health," addresses contact with and consumption of marine toxics, harmful phytoplankton, and fecals/pathogens.

Topic	Stressor	Current Effort
Contamination		
1. *Toxics*	add toxics	X
2. *Nutrients/Pathogens*	add nutrients	X
	contribute fecal coliform bacteria	X
	increase marine debris	
	increase air deposition	
Physical Environment Alteration		
3. *Inputs to nearshore and pelagic habitat*	increase sediment loadings	X
	decrease sediment loadings	X
	alter freshwater output	X
	increase strength of peak flows	X
4. *Ambient changes in nearshore and pelagic habitat*	alter light transmissivity from turbidity	X
	cause shading (structures)	
	produce noise	
	create physical disturbance via intrusion	
	change depth or shoreline slope	X
	alter sediment type, include: via water transport	X
	physically disturb the sediments	
	resuspend sediment	
	reduce endemic benthic habitat area	X
	sea level change	
	add constructed habitat	X
	alter seawater temperature regime	X
	impede water circulation	X
Organisms		
5. *Marine biota*	extinction/threatening of marine species	X
	introduction of exotic marine species	X
	alter local marine species composition	X
	change marine organism abundance	X

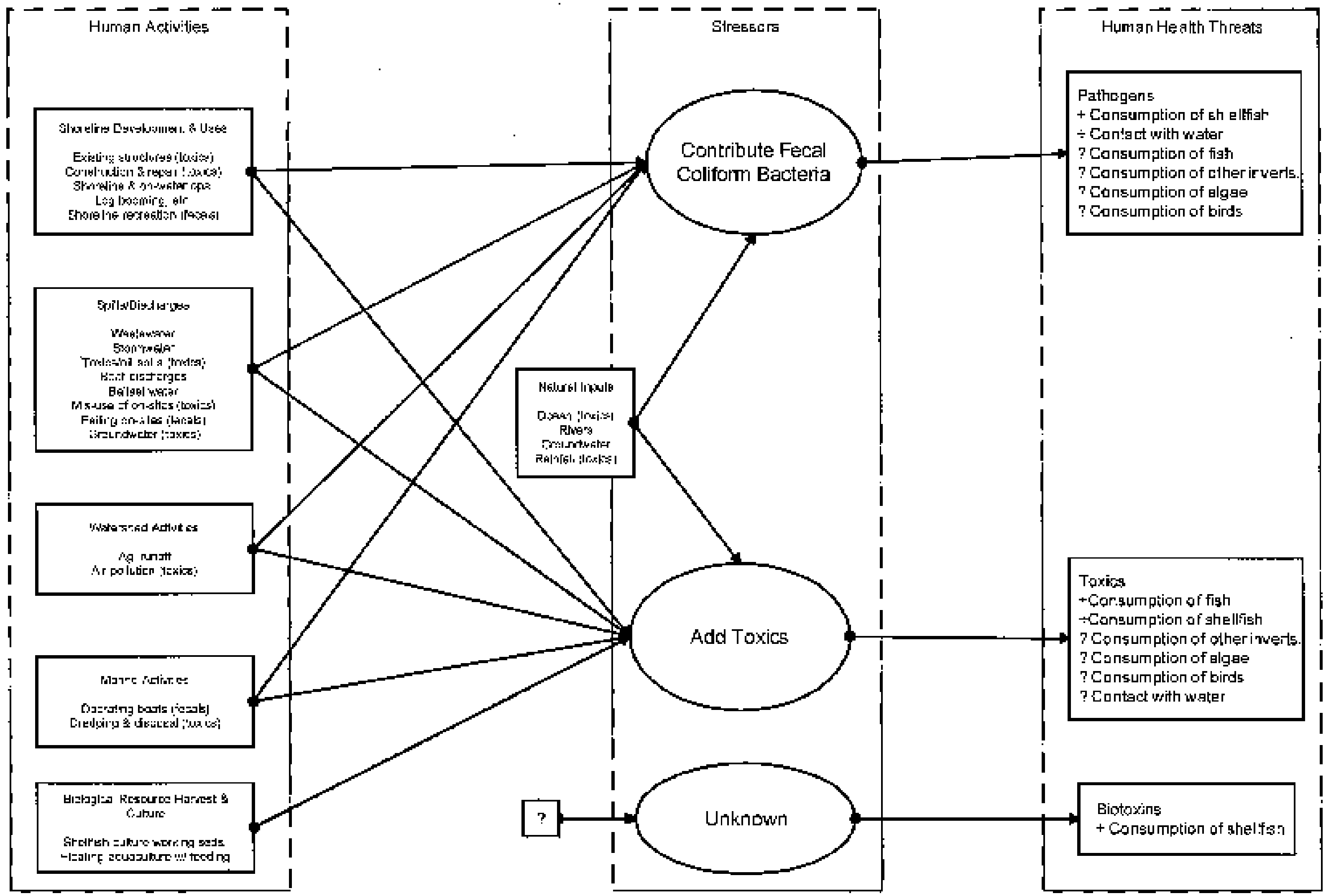

Figure 5. Conceptual model of human health threats in Puget Sound.

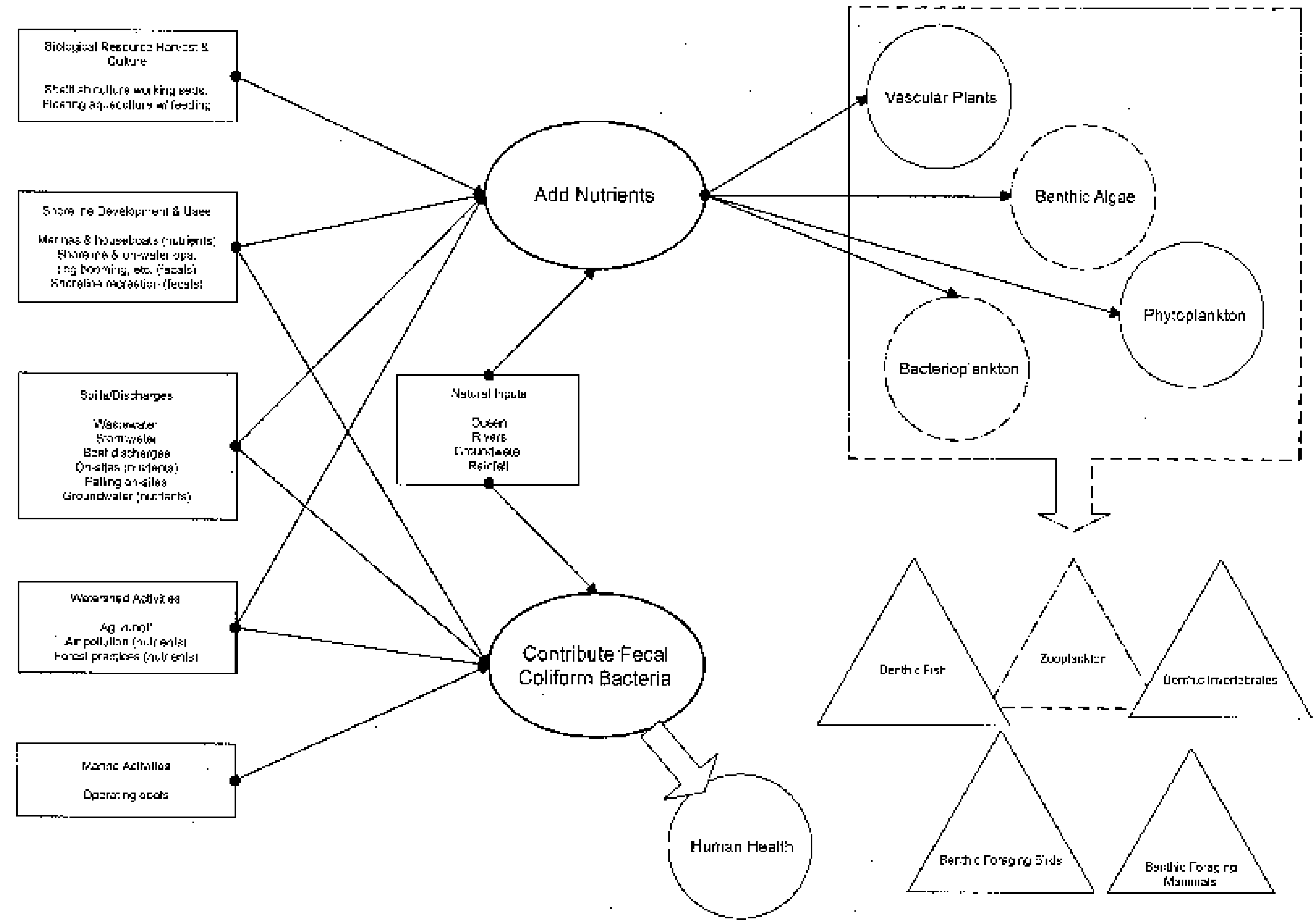

Figure 6. Conceptual model of nutrient and pathogen stresses in Puget Sound.

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