

Kiker, G.A. and Linkov, I. (2006). The QnD Model/Game System: Integrating Questions and Decisions for Multiple Stressors. (Chapter in Arapis, G., Goncharova, N., and Baveye, P. (Eds) "Ecotoxicology, Ecological Risk Assessment and Multiple Stressors" Springer, Amsterdam. Pp:203-226.

The QnD Model/Game System: Integrating Questions and Decisions for Multiple Stressors

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Abstract

Complex environmental challenges include elements of social and cultural viewpoints as well as the often-explored technical viewpoint. The *Questions and Decisions*™ (QnD™) screening model system was created to provide an effective and efficient tool to integrate ecosystem, management, economic and socio-political factors into a user-friendly model/game framework. The model framework is utilized in a larger process of stakeholder participation in order to generate questions and decisions for the management of complex environmental challenges.

The model is written in object-oriented Java and can be deployed as a stand-alone program or as a web-based (browser-accessed) applet. The QnD model links spatial components within geographic information system (GIS) files to the abiotic (climatic) and biotic interactions that exist in an environmental system. QnD can be constructed with any combination of detailed technical data or estimated interactions of the ecological/management/social/economic forces influencing an ecosystem. The model development is iterative and can be initiated quickly through conversations with users or stakeholders. Model alterations and/or more detailed processes can be added throughout the model development process.

Two examples are described to show QnD applications within risk and contaminant problems. QnD:ARAMS provides simple integration of elements from the ARAMS risk modeling system to simulate risk and ecosystem-related features. QnD:HAAF was developed to integrate field experiments in order to generate a methylmercury balance model for simulation of restored saltwater wetlands. Lessons from the use of QnD in the case studies show that the value of integration modeling is often more than the prediction of future events. The QnD model and its integration process are useful in identifying some of the critical features of ecosystems while still appreciating the

complexity involved in making management decisions.

1. Introduction

Environmental decision-makers are coming to the realization that the solutions to complex environmental problems are complicated by the need to take action that simultaneously minimizes risk and uncertainty while maximizing stakeholder acceptance and societal value. Within the practice of environmental management, "wicked" problems (Rittel and Webber, 1973) are commonplace. Yoe (2002, p. 2) describes wicked problems as those "that do not have a right or wrong answer but only answers that are better or worse. Wicked problems are found at the intersection of science and values." A great many of the problems addressed by environmental managers are inherently wicked and require an integration of scientific information, uncertainty estimation, and social/cultural valuation for environmental decision-making.

Decision-makers and scientists often believe that complex environmental problems require the development and use of complex systems models. However, simple, pragmatic models that require fewer parameters than complex models can be useful in ecological studies (Jeppesen and Iversen, 1987). This simple-model approach was useful in highlighting selected management issues within the Colorado River ecosystem (Walters et al., 2000), where a suite of simple models at multiple scales of time and space were used to assist scientists and managers.

The idea of management as a "game" involving different roleplayers and options, can reveal important general patterns of system behavior (Carpenter et al., 1999). Carpenter describes a simple model of ecosystem management from the perspective of selected roleplayers. This model serves to show the interaction between fast and slow variables (multiple time scales), and illustrates the point that continual learning is crucial for sustainability. However, this model lacks a spatial component, and is specific to a single lake ecosystem. Starfield et al. (1993) presents a frame-based modeling approach, which consists of collections of smaller models representing different states (frames) within a single system. Different frames are invoked according to certain sets of conditions and rules. Our experience shows that simple models are made more applicable to complex environmental management through the inclusion of a spatial component. Spatially explicit modelling is useful in quantifying patterns and linking them to ecological processes and mechanisms (Matsinos et al., 1994).

In designing the QnD model, we have chosen to develop an intermediate-scale management "game" model that is useful in assisting scientists and managers to generate questions and decisions for complex environmental management. The QnD approach utilizes simple connections, rules and relationships to model complex systems.

The three objectives of this chapter are the following:

- Briefly describe the design and application methodology of the Questions and Decisions (QnD) model
- Explore the use of the QnD model to describe two different ecosystems
- Highlight the lessons learned and next steps for QnD development

2. QnD Model Structure

The *Questions and Decisions*™ (QnD™) screening model system (Kiker et al., 2005) was created to provide an effective and efficient tool to integrate ecosystem, management, economics and socio-political factors into a user-friendly model framework. The model is written in object-oriented Java and can be deployed as a stand-alone program or as a web-based (browser-accessed) applet. The QnD model links spatial components within geographic information system (GIS) files to the abiotic (climatic) and biotic interactions that exist in an environmental system.

The model can be constructed using any combination of detailed technical data or estimated interactions of the ecological/management/social/economic forces influencing an ecosystem. The model development is iterative and can be initiated quickly through conversations with users or stakeholders. Model alterations and/or more detailed processes can be added throughout the model development process. QnD can be used in a rigorous modeling role to mimic system elements obtained from scientific data or it can be used to create a "cartoon" style depiction of the system to promote greater learning and discussion from decision participants.

The QnD system is divided into two parts: the game view and the simulation engine as shown in Figure 1. The game view has several types of outputs that can be configured by the user via XML (eXtensible Markup Language) file inputs. By presenting the outputs as selectable, QnD allows users to choose how they want to see their output, including the following output options as described in Figure 2:

- Maps that are updated on each time step
- Warning lights that change at user-selected critical levels
- Mouse-activated charts and text for individual spatial areas (pie charts and text line descriptions)
- Time-series charts (listed on several tabbed pages)
- Text output files (in comma separated format)

The simulation engine of QnD is made of a few basic objects linked together into simple or complex designs, determined by the needs of decision participants. The most elemental objects of QnD are Components, Processes and Data as shown in Figure 1. A Component is an object that is of interest to the user. Processes are the actions that involve Components. Data are the descriptive objects assigned to Components. If one uses parts of grammar as an analogy, Components are the nouns. Processes are the

verbs. Data objects are the adjectives or adverbs. For clarification, a "C" prefixes Components, a "P" prefixes Processes, and a "D" prefixes Data objects. For example, the statement "A lion kills two impala per day" could be interpreted as the Components (**CLion** and **CImpala**) with a Process ("**PKill**") and Data (**DLionPopulation** and **DImpalaPopulation**). In this case, the Process "**PKill**" would use the **DLionPopulation** to calculate the reduction in the **DImpalaPopulation** (by $2 \times \text{DLionPopulation}$).

Simulation Engine

- Developer's point of contact
- Objects: Components, Processes and Data
- Calculation for selected time step

Game View

- User's point of contact
- "Widgets": Maps, Charts, Warning Lights, Text, Sliders, Icons, Buttons
- User choices – management settings, simulate fast or slow time step, reset

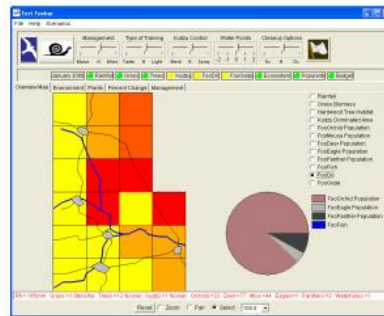
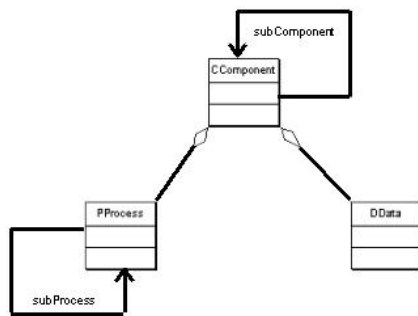


Figure 1. QnD model main parts: "Simulation engine" and "Game View."

The relationships among the most fundamental building block components in QnD include CWorld, CSpatialUnits, CHabitats, Organisms and Chemicals are described in Figure 3. The CWorld object contains all the objects and serves to define the spatial limits of the simulated system. A CSpatialUnit is the basic spatial unit of the QnD system. CSpatialUnits are linked to one another and have a specific location. A CSpatialUnit can have either zero or any number of CSpatialUnits connected to them. In addition, these connections can be labeled with useful words to group similar types of connections. For example, a riverine description may be "UPSTREAM" to describe all connections that move against a prevailing current. CHabitats exist within CSpatialUnits and are not spatially defined. CHabitats make up a certain percent area of a CSpatialUnit. At least one default habitat exists (and occupies 100% of the CSpatialUnit) if the user does not set up any other CHabitats. A CHabitat can hold any number of COrganisms or CChemicals. With the QnD object framework, both simple and complex designs are possible. In more complex designs, building block components and processes designed as clusters of subcomponents or subprocesses.

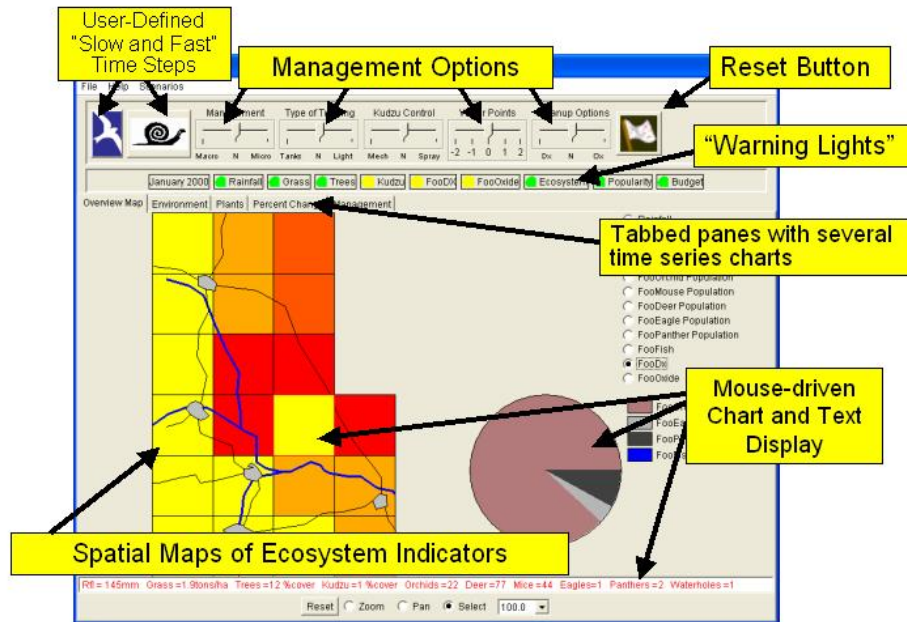


Figure 2. QnD Game View features.

Upon startup, specialized internal QnD objects read the relevant XML input files and create all the engine parts (Components, Processes and Data) as well as the game view (maps, charts and management options) required for the simulation. Once all the necessary parts are created, QnD is "played" much like any other computer games. Users can manipulate the game view in the following ways:

- Set some management options (using the slider bars)
- View the map page and switch between maps (with radio buttons)
- View the various Chart pages (with the chart tabs)
- Simulate a time steps at user-defined levels
- Reset the game to the startup

Management settings are applied to the current time step that is activated by mouse-clicking on either of the two time step buttons as shown in Figure 2. After clicking on the time-step button, results of the simulation are applied to the various output devices (maps, charts, warning lights, text files etc...). The user can then explore the system outputs, choose new management options and continue with the simulation. Certain end points can be created to show various ramifications of management actions. In

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Kiker *et al.* (2005), QnD end points showing ecosystem destruction, bankrupt financial status or employment termination were used to show the various end points of ecosystem management in African savanna ecosystems.

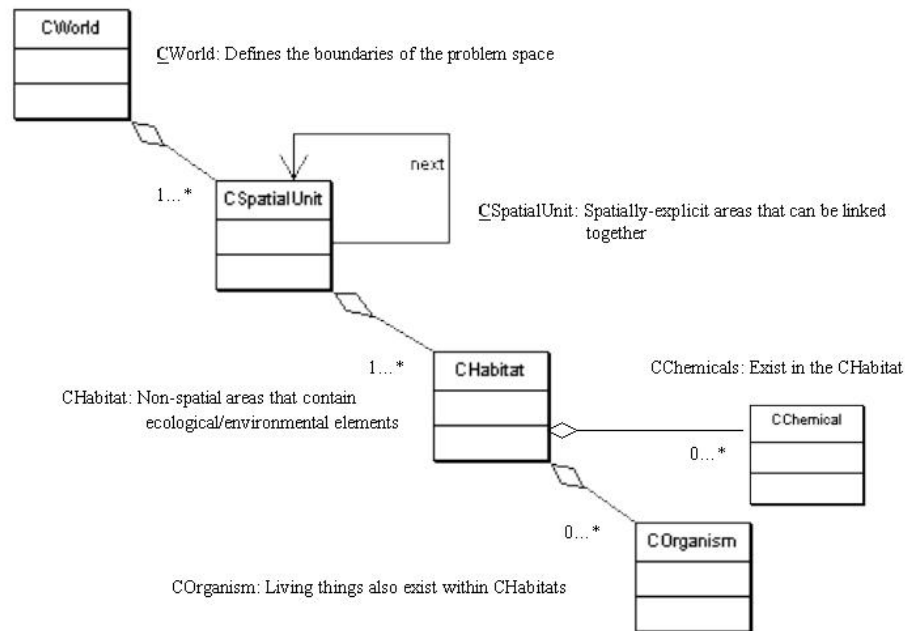


Figure 3. QnD Simulation Engine: basic object design.

3. QnD Development and Methodology in Environmental Decision-Making

The QnD model is included in a larger process of stakeholder participation when used to iteratively generate questions and decisions for complex environmental management. A more detailed description of this overall QnD development and application methodology is presented in Kiker *et al.* (2005). Development of a QnD game and its application was inspired by some of the principles described by Gunderson *et al.* (1995), Gunderson and Holling (2002) and Checkland (1999) to view the problem from a variety of technical, social and cultural perspectives. Three activities to develop and use a QnD model/game are outlined below.

1. Describe the problem and its parts in words and pictures

Through conversations with stakeholders, a series of pictures, stories, experiences, simple diagrams or equations are recorded to get an overall view of the problem. The

QnD developer asks focused questions the ecosystem, management options/challenges, external constraints or influences including budgetary and political factors. In this manner, the QnD developer builds a "rich picture" (Checkland, 1999) as a means of exploring the problem situation from a variety of viewpoints and perspectives. This first activity is used to formulate the basic QnD world in that the various pictures described can be used to create the objects needed for the first iterations of the game/model. QnD's modular structure allows a variety of object designs so that initial ideas can be iteratively changed or discarded with minimal impact on other modules.

2. Interpret the words and pictures into QnD objects

The various system descriptions from activity one are used by the QnD developer to fashion the initial engine and game view sections. An essential element of the QnD model is that the game view should be constructed as much as possible from the user's perspective while the engine can be a combination of technical and subjective relationships. Quite often traditional scientific modeling design forces the stakeholders to adopt the model's frame of reference, jargon and philosophy. While QnD does have its own jargon and design (CComponents, PProcesses and DData for example), these are used at minimal levels by QnD developers. Stakeholders do not interact with the engine design, but rather view the QnD model through the game interface (see Figure 2).

3. Discuss and debate the problem situation using QnD

The third activity is using QnD to generate discussion and debate in order to identify desirable and feasible actions and changes that would improve the problem situation. This discussion in which stakeholders interact with various QnD elements may highlight three resulting activities: (1) changing the QnD engine to provide a more adequate simulation of measured events; (2) changing the QnD game view to better represent management information requirements or potential actions; or (3) identifying new aspects of the problem situation that were previously hidden from scrutiny. By playing QnD scenarios, users find that they are able to explore the positive and negative repercussions related to each potential management option. Participants are able to discuss both informal "rules of thumb" and technical aspects of management decisions. In addition, QnD enables stakeholders to explore from a variety of perspectives how a decision might impact ecosystem components as well as socio-political and economic factors.

4. QnD as an Integrator of Multiple Stressors: Two Examples

Two examples of QnD as an integrator of multiple stressors are presented in this section. The first case study shows how a simple QnD model can be used to enhance and extend the components of a risk model (ARAMS) into further, ecologically-related modeling products. The second case study, presented in greater detail, shows QnD

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performing a more complex integration of field-based studies to establish a model of mercury dynamics in a tidal wetland.

4.1 QnD:ARAMS – Integration with a risk model for exploring ecosystem effects

ARAMS, an adaptable risk assessment modeling system was developed by the US Army Corps of Engineers (Dortch, 2001; Dortch and Gerald, 2004; Gerald and Dortch, 2004) to provide tools to perform human and ecologically based risk/hazard assessments. The objective of ARAMS is to provide a platform from which a variety of risk assessments can be performed, allowing users to visualize an assessment from source through multiple environmental media (groundwater, surface water, air, and land) to sensitive receptors of concern (e.g., humans and ecological endpoints).

As a tutorial exercise in ARAMS, Dortch et al. (2004) constructed an example of an aquatic ecological assessment based on user-defined water concentration and dose-duration data derived from the Wildlife Ecological Assessment Program (WEAP) model (Whelan et al., 2000). The exercise explores the use of time-varying surface water concentrations (4-nitrophenol) with WEAP to determine the ecological impact on aquatic life, specifically rainbow trout (*Oncorhynchus mykiss*). This ARAMS example calculates the percentage of time that an aquatic species is exposed to 1) acceptable impacts, 2) unacceptable impacts with less than 50 percent physiological effects, and 3) unacceptable impacts with equal to or greater than 50 percent physiological effects. The output also summarizes the probability of equaling or exceeding a concentration based on exposure duration.

The primary objective of this QnD example is to explore the integration of the QnD model with risk assessment models. Traditional ecological risk assessment is described graphically in Figure 4A (adapted from USEPA, 1997; MERAC,1999) and follows several stages including: Planning, Problem Formulation, Analysis, Risk Characterization, Risk Communication with Risk Manager, Risk Communication with Stakeholders. Figure 4B shows the potential linkage between ecological risk assessment, its associated risk models (such as ARAMS), and the QnD system. In addition, Figure 4B provides a conceptual figure of the QnD:ARAMS model. The ARAMS model provides some of the inputs to QnD's engine components such as the input time series, data values, and dose-response relationships. The QnD system expands the single contaminant-to-fish pathway simulated by the ARAMS model by providing a spatial area for multiple populations and additional simulated items that provides greater detail in fish responses to contaminant concentrations.

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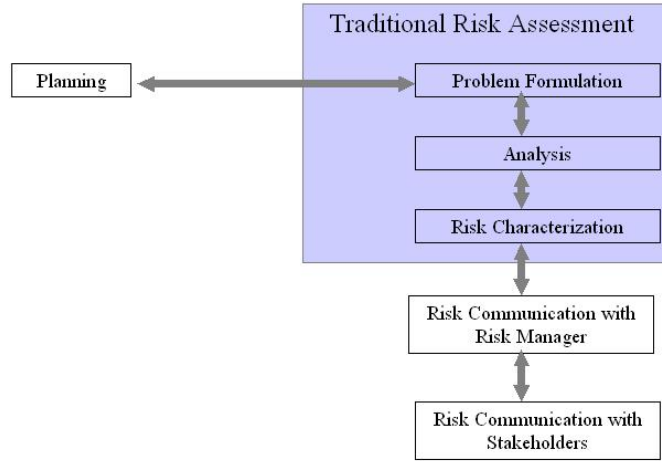


Figure 4a. Methodology for ecological risk assessment (adapted from MERAC, 1999).

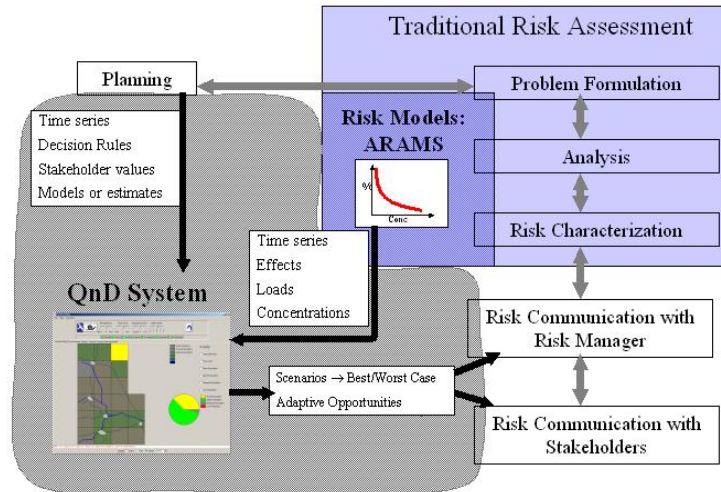


Figure 4b. The QnD model integrated with ecological risk assessment models and data.

4.1.1 QnD:ARAMS - Design

Figure 5 shows a diagram of the engine components of QnD:ARAMS along with a picture of the game view. There are eleven river reaches that are simulated with one default habitat within each river reach. Rainbow trout within each river reach are simulated as a local group or metapopulation. Each local trout group is described by data objects including population, condition index, consecutive days of exposure over a chronic effects limit, consecutive days of exposure over an acute limit, and consecutive days under any limit.

In QnD:ARAMS, the processes describe the various effects on the 4-nitrophenol concentrations on trout populations. A summary of processes is listed below:

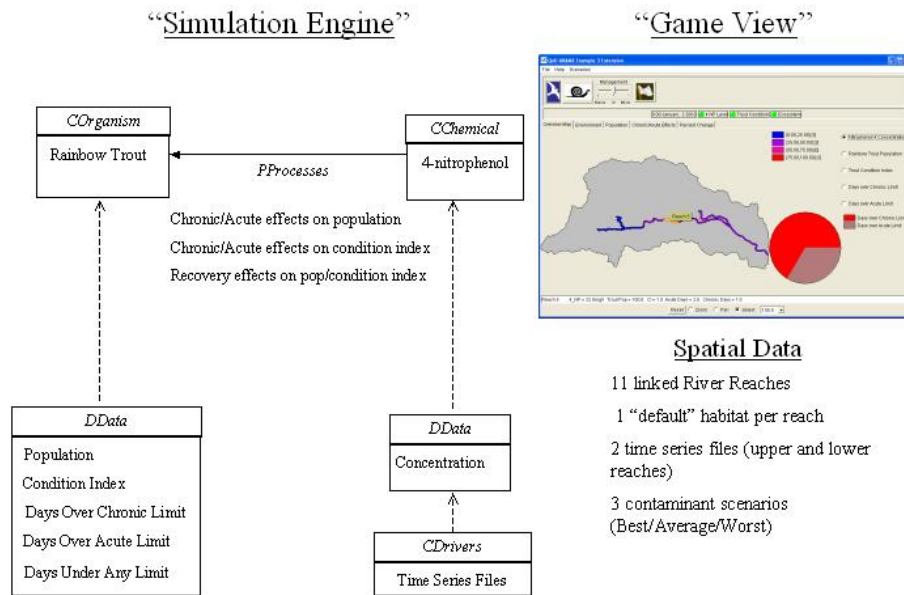


Figure 5. Object diagram of the QnD:ARAMS model.

- Driver Processes
 - Use the daily 4-nitrophenol concentration to calculate the number of days over chronic (10 mg/L) and acute (50 mg/L) limits as well as the days under any limit.
- Rainbow Trout Processes
 - Effects on trout condition index:
 - Use the days over chronic limit to influence the condition index negatively
 - Use the days over acute limit to influence the condition index negatively
 - Use the days under any limit to influence the condition index positively
 - Effects on trout population:
 - Use the days over acute limit to create a sharp reduction in population
 - Use the condition index to alter population positively or negatively

The spatially-explicit modeling allows the simulation of different populations within the eleven reaches with time series inputs of concentrations from two different water quality recording stations. By constructing three basic contaminant scenarios (normal, worst and best case) each with its own time series file, a variety of cases can be simulated. The time series files containing 4-nitrophenol contaminant inputs in the water from the ARAMS model are the primary drivers.

In the initial version of QnD:ARAMS the game view was kept simple with only warning lights showing thresholds for acute and chronic levels, and mouse-driven pie charts and text to show ratios of number of acute and chronic days. Each trout population was initialized at 1000 fish per reach.

4.1.2 QnD:ARAMS - Discussion

A sample of QnD:ARAMS outputs are summarized in Figure 6(a-d) showing the effects of time series concentrations (normal scenario) on two example trout populations in two of the eleven reaches (Reaches 1 and 5). Figure 6a describes the populations, figure 6b shows the calculated condition index, figure 6c illustrates the days over chronic and acute limits and figure 6d shows the daily concentrations in the two selected reaches.

Both reaches have similar concentrations for the first twenty days of simulation. The concentration in both reaches is sufficiently high enough to cause an immediate decrease in overall condition as realized in the decrease in the condition index. Reach 1 shows another higher concentration spike which increases the number of days over the acute limit and subsequently precipitates a sudden population decrease of about 15% on day 25 (Jan 25). After this event, the subsequent concentrations in Reach 1 are enough

to keep the condition index at a minimum level. Trout populations in Reach 5 encounter mostly variations in condition index with no large die-off as seen in the Reach 1 population. The subsequent lower concentrations allow the Reach 5 trout to recover to higher condition index values.

One interesting feature of these demonstration simulations is the resilience of the simulated populations over a variety of concentration pulses. This resilience may have several explanations including: (1) an artifact of the QnD model design, (2) an unintended feature/nuance of ecosystem performance or (3) a purposefully designed aspect of stakeholder/scientific intent. In any case, the initial results such as those in Figure 6 can be discussed among users and modifications can be made to either component, process or data object design or to the initial data values themselves. This freedom to quickly change internal model parts or values through the XML input files allows new ideas to be quickly designed, tested and implemented.

The major effort within the integration of ARAMS and QnD is deciding what ARAMS-related information will map to the appropriate QnD components, processes and data objects. ARAMS is configurable and expandable within the limits of its modular programming platform, which has specific and rigorous requirements for software operating within its environment. Integration of model codes and formats is a continuing challenge to almost all model linkage efforts. QnD can provide a combination of simulated fish/contaminant interactions with the more human aspects of culture and societal reaction. The ability of QnD:ARAMS to simulate shorter or longer time steps allows for more exploration of potential management/mitigation activities such as reach-specific cleanup efforts or dilution effects due to water releases.

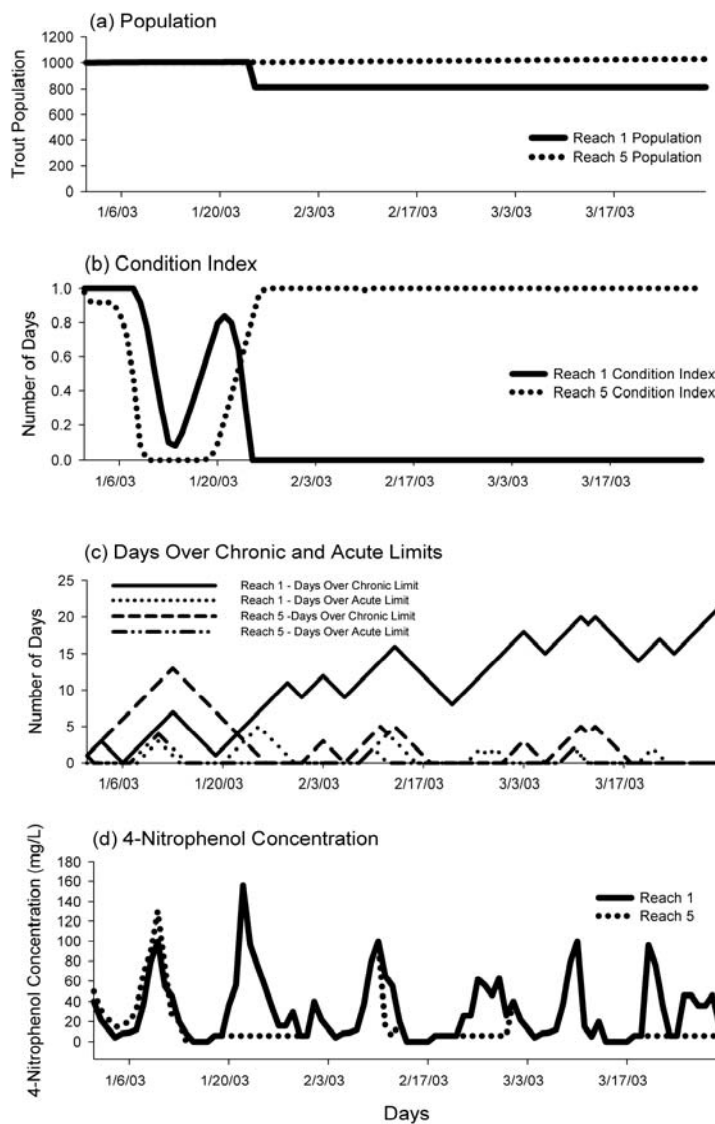


Figure 6. Sample results from QnD:ARAMS simulations.

Another important aspect of the QnD:ARAMS example simulation is that it can service other important decision factors in addition to the risk-related factors created by ARAMS. The role of iteration is strengthened with QnD as concepts can be quickly altered with the XML input files. Entirely new organisms, chemicals can be formulated with their own processes and data without affecting existing components, processes and

data objects. Each new addition to QnD:ARAMS processes will require discussion and testing. For example, trout movement between reaches so that there is some intermixing of metapopulations will present challenges on how to combine populations of differing condition or health.

Finally, questions related to adaptive management might be addressed through the stakeholder input and testing of QnD:ARAMS. Various chemical mitigation options could be defined and implemented as management options to allow responses such as fish advisories, altered flow regimes or cleanup options. Each QnD:ARAMS iteration can be used to explore various ecosystem and human dynamics.

4.2 QnD:HAAF – A Screening-Level Model Design for Integrating Physical, Chemical and Biological Processes that Drive Mercury and Methylmercury Cycling

Stakeholders involved in wetland restoration activities on the former Hamilton Army Air Field (HAAF), located near San Francisco, California (USA), aim at restoring San Pablo Bay wetland habitat, while minimizing conditions for methylmercury production and its subsequent trophic transfer to San Francisco Bay fisheries. However, sufficiently detailed information on environmental mercury levels at HAAF are lacking, as well as a mechanistic understanding of the factors that control these levels and the means to use this information in ecosystem models supporting environmental management decisions.

The purpose of the QnD application to the HAAF site (QnD:HAAF) is to integrate the field and laboratory data and facilitate the use of these data as a basis for screening-level predictions for (1) other coastal wetland sites, and (2) "scaling up" for landscape-scale simulations. QnD:HAAF is being applied in an iterative, interactive manner to identify critical abiotic and biotic drivers of salt marsh mercury and methylmercury cycling and guide subsequent work on HAAF and San Francisco Bay salt marshes (Best et al., 2004). As further learning occurs from subsequent studies, those ecosystem drivers that are shown to be important can be explored and subsequently expanded, those judged less important can be discarded. While these major structural changes would require substantial code rewriting of other models (e.g., Mercury Cycling Model; Hudson et al., 1994), these changes are made rapidly in QnD. QnD achieves modeling nimbleness by keeping compartments, processes and interactions conceptually simple. Thus, the QnD:HAAF system can serve as a capstone for integrating monitoring results into a more management-focused model.

The initial version of QnD:HAAF is focused on exploring consensus technical questions formulated at the past stakeholder-derived questions including:

1. What are the present levels of MeHg in San Francisco Bay wetlands with respect to biota and sub-habitats, and location within the Bay?
2. What are the rates of MeHg production?

3. What factors control MeHg production? Can these be managed?
4. Are some wetlands larger mercury exporters than others?
5. Can we model/predict the effects of wetland restoration on MeHg production and export?

The various objects used in the initial version of QnD:HAAF are presented in Figure 7. These objects (Chemicals, Organisms and Drivers) exist within a 'virtual' landscape of spatial areas and habitats. The Chemical and Organism objects participate in specific processes that cause changes in the ecosystem. For example: within a High Marsh (spatial area object), a crab (organism object) may take MeHg up from the sediment (chemical object). An extended description of the QnD:HAAF model, including the data with which it was calibrated originally, is presented in Best et al. (2004) . The following sections provide a summary of the various processes described in Figures 7 and 8.

4.2.1 Spatial Areas and Habitats

While QnD can simulate ecosystem components and processes for an entire map of linked spatial areas, the initial version of QnD:HAAF utilizes four stylized wetland areas (Figure 8). This spatial simplification allows the use of the data of initial feasibility studies with simplified modeling concepts, instead of attempting to fit a complex model to an ecosystem in which no data have been collected. In QnD:HAAF, the selected scale of each spatial area is 10 x 10 m (100 m²), all mass data are on a dry weight basis, and all simulated data are on a m² basis.

In Figure 8, the "High Marsh" area represents *Salicornia virginica* (pickle weed)-dominated areas that are rarely flooded. The "Mid Marsh" area represents *Spartina foliosa* (cord grass)-dominated areas that are partially flooded as a part of the daily tidal cycle. The third spatial area represents the "Mud Flat" zone that is partially submerged. The fourth spatial area represents the "Sub Tidal" zone that is completely submerged. Each spatial area has resident biota listed in Figure 8. In the initial version of QnD:HAAF, no specialized habitats within the spatial areas are distinguished, i.e. one "default" habitat occupies 100% of the spatial area.

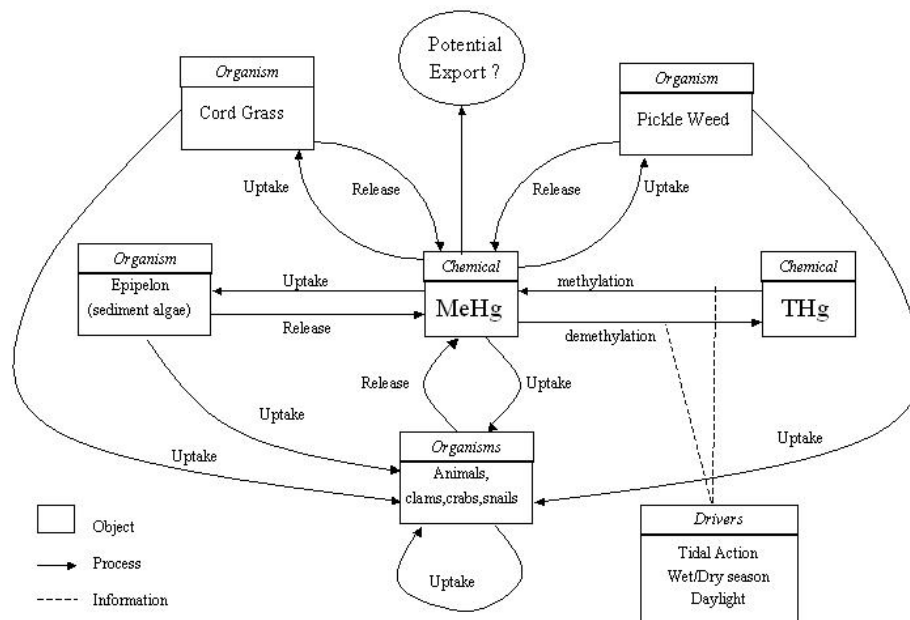


Figure 7. Object diagram for the QnD:HAAF model.

4.2.2 Environmental Drivers and Time Scales

Three environmental drivers were selected to link processes at time scales varying from hourly to seasonal. An on-line tide simulator for the bay area was used to provide initial estimates of tidal water levels for selected time periods on an hourly basis (<http://tbone.biol.sc.edu/tide/sitesel.html>). For initial QnD:HAAF testing, two hourly time series were constructed, representing a dry season, i.e. 1 – 14 June 2003, and a wet season, i.e., 1 – 14 February 2004), respectively. QnD:HAAF utilized a default time step of one hour.

4.2.3 Tidal and Redox Processes

Water depth on each spatial area is calculated by subtracting its' local sediment elevation hourly from the tidal water level. If the calculated local water depth has a positive sign, then the spatial area is considered as being submerged and susceptible to decreasing oxygen diffusion. Vice versa, if the calculated local water depth has a negative sign, then the spatial area is considered as extending above the water level and thus susceptible to oxygen diffusion from the ambient air. The cumulative numbers of hours under and above the water level, respectively, are used to calculate the hourly change in redox potential (mV). The hourly change in redox potential is then added to the cumulative redox potential for each spatial zone.

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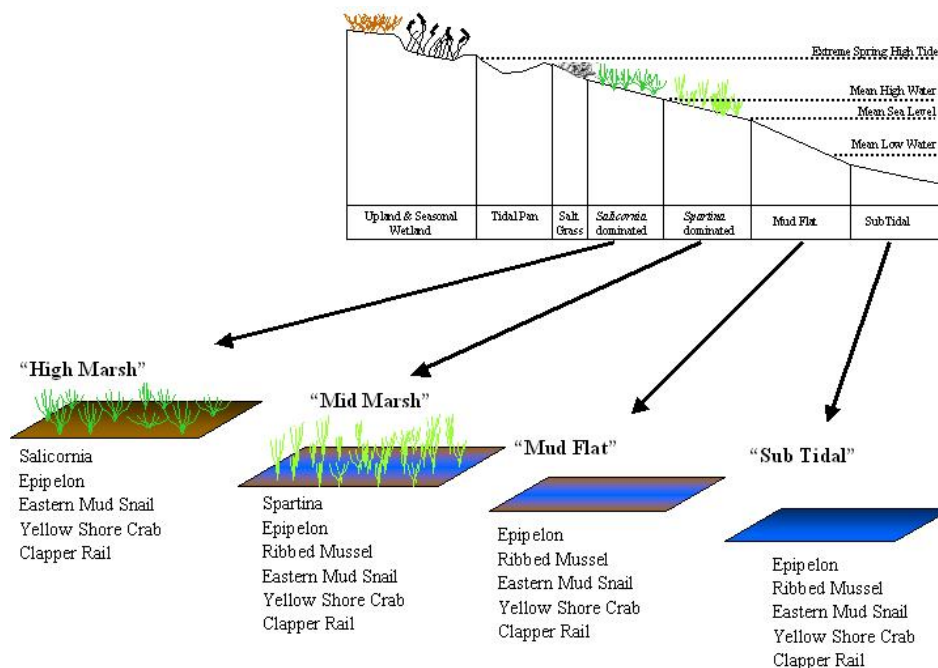


Figure 8. Spatial areas in the QnD:HAAF model.

4.2.4 Mercury Dynamics

Two chemical mercury pools are assumed to exist and are available for transformation: total mercury (THg) and methylmercury (MeHg) as described in Figure 7. Both pools are assumed to reside in the surficial 5-cm sediment layer and its associated pore water. The pools change in mass per unit area (ng m^{-2}), but have an associated, calculated concentration (ng g^{-1}). The pools are considered as fully active, i.e., the whole THg pool is available for conversion into the MeHg pool, and vice versa. THg is transformed into MeHg as a function of time of year (dry or wet season), redox potential (dependent on tidal movements) and time of day (light or dark conditions). MeHg is demethylated and returns as Hg to the active Hg^{2+} pool following a simplified, first-order, rate equation (DTMC/SRWP, 2002), which is affected by redox potential, tidal water movements, season, and light/dark conditions.

In QnD:HAAF, MeHg is exported from the sediments at a constant rate. This amount of MeHg exported enters into a general pool that quantifies any potential MeHg export.

4.2.5 Biota and their Processes

Selected organisms are included in the QnD:HAAF model, i.e. plants, invertebrates, and one bird species (Figure 8). Two emergent macrophytic plant species and one

microalgal group are represented in the current version of QnD:HAAF. *Salicornia virginica* (Pickle weed) and *Spartina foliosa* (Cord grass) are simulated at the simplest level as an established standing crop with constant biomass. Plant MeHg load (ng) and potential contribution to export were assumed to be the primary data of interest in these simulations. The epipelton (algae living on the sediments) are also potential contributors to the export of MeHg. The following wetland invertebrates are modeled as potentially resident in all four spatial areas, but with population size and biomass being spatial area-specific: Ribbed Mussel (*Geukensia Demissa*), Yellow Shore Crab (*Hemigrapsus Oregonensis*) and the Eastern Mud Snail (*Iyanassa obsoleta*). These animals have been identified in field samples. For exploring the trophic transfer and bioaugmentation of MeHg to higher levels in the food chain, the California Clapper Rail (*Rallus longirostris obsoletus*) is included as potentially resident in all four spatial areas. For the initial version of QnD:HAAF, it is assumed that biota do not migrate between spatial areas.

In this initial QnD:HAAF version, the relationships between consumers and their food sources are formulated as a predator-prey relationship. According to this approach, when a mud snail grazes epipelton, the mud snail would be a predator and the epipelton would be a prey. Long-term changes in biomass due to growth and respiration are not included. The biomass of plants (*Salicornia*, *Spartina* and epipelton) and ribbed mussels is assumed to be constant within the two-week simulation period.

4.2.6 Biota Uptake of MeHg from Sediment

In QnD:HAAF, all biota have uptake and loss processes that allow them to potentially bioaccumulate and release MeHg. This methodology is in accordance with DTMC/SRWP (2002), recommending an initial simplified approach, followed by a detailed bioenergetic approach once MeHg data become available on higher trophic levels. Data on uptake and bioaccumulation of MeHg from soil, sediment, and pore water are still extremely scarce in the literature, and they are, therefore, largely estimated from HAAF field experiments and from relevant literature (Mason et al., 1996; Rogers, 1994; Barber, 2001).

4.2.7 Biota Uptake of MeHg from Grazing or Predation

Uptake of MeHg by ingestion of biotic food sources is calculated from the biomass ingestion. Each food source with MeHg that is consumed is transferred from predator to prey. Accordingly, the MeHg contained in the prey biomass is also transferred to the predator.

4.2.8 MeHg Loss From Biota

It was estimated that all plants lose 50 percent of their biomass per year and, based on this estimate, they would also lose that fraction of the MeHg contained in the plant biomass. In QnD:HAAF all plants, i.e. macrophytes and epipelton, are modeled as losing 50 percent of the MeHg contained in their maximum standing crop per year. All animals, including the ribbed mussels with constant biomass, are assumed to release 10

percent of their resident MeHg load per day. This amount of MeHg released enters into a general pool that quantifies the potential MeHg export.

4.2.9 QnD:HAAF Discussion

The purpose of the QnD:HAAF model is to integrate the field and laboratory data collected in other studies on the HAAF site, and to identify critical abiotic and biotic drivers of salt marsh mercury and methylmercury cycling. In addition, QnD results and on-going interactions with both scientists and other stakeholders help to guide further monitoring and management on HAAF and San Francisco Bay salt marshes.

The current version of QnD:HAAF is composed of four spatial areas (High *Salicornia*-vegetated Marsh, Mid *Spartina*-vegetated Marsh, Mud Flat, and Sub Tidal), three drivers (day-time light, dry and wet season, and tide-dependent redox potential), and two processes (methylation and demethylation), and biota, represented by typical plant and animal species.

Two fourteen-day scenario's were simulated using QnD, i.e., one scenario representing the wet season (Feb 1 –14, 2004) and one scenario representing the dry season (June 1 – 14, 2003) as shown in Figure 9. Methylation and demethylation rates varied widely over time and space primarily due to tidal effects as Figure 9 highlights. Other QnD results showed simulated MeHg levels in biota indicated a significant bioaccumulation potential from lower to higher trophic levels, regardless of season. Simulated MeHg concentrations in the sediment exceeded the field-measured levels although the simulated methylation and demethylation rates were in the same order of magnitude as published values. One potential factor for the MeHg buildup may point to a missing export factor beyond the simplified approach in the first QnD:HAAF version. Elevation proved to be an important factor influencing net MeHg production, reflected in the far higher methylation and demethylation rates in the *Spartina*-vegetated Marsh and Mud Flat than in the *Salicornia*-vegetated Marsh and Sub Tidal areas.

In the initial version of QnD:HAAF, the primary stakeholder group was the scientific team that conducted the field studies. Accordingly, the design of QnD followed a more technical path for exploration of what data was required to frame the problem in a systematic fashion. In further versions, it is planned to incorporate and link the scientific/monitoring results with more economic and social issues for simulating different MeHg management scenarios.

4.3 QnD Discussion – Lessons Learned

The *Questions and Decisions*™ model system was created to provide an effective tool to incorporate ecosystem and management issues into a user-friendly framework. This chapter highlighted two case studies in the use of QnD to generate questions and decisions for complex environmental challenges.

Kiker, G.A. and Linkov, I. (2006). The QnD Model/Game System: Integrating Questions and Decisions for Multiple Stressors. (Chapter in Arapis, G., Goncharova, N., and Baveye, P. (Eds) "Ecotoxicology, Ecological Risk Assessment and Multiple Stressors" Springer, Amsterdam. Pp:203-226.

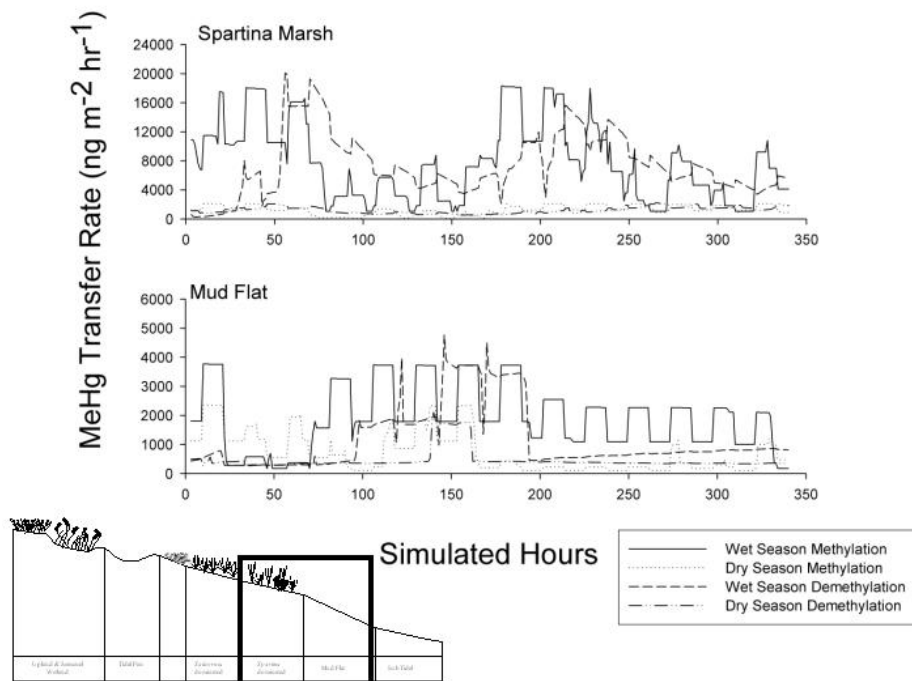


Figure 9. Sample results from QnD:HAAF simulations.

QnD:ARAMS used a simple object design to link elements of a risk model into an ecological modeling/decision framework. Two main lessons emerged from the development of QnD:ARAMS described below.

QnD Lesson One: Combining the elements of two or more models requires an understanding of each model's basic frame of reference. ARAMS used the risk assessment paradigm to organize its information and generate output that speaks primarily to risk assessors. This framework is different than watershed and ecosystem models that use a process-based, spatial structure that influences the QnD object structure. These fundamental framework differences made it challenging to move statistical and risk outputs from ARAMS into QnD objects. Risk model outputs such as the percent exceedance of a chronic effects level are not successfully mapped into QnD objects, unless all mapped objects are stochastically created by QnD. If a QnD developer wishes to construct a process that describes chronic effects, they would have to use the same time series and other inputs to create a new chronic level calculation within QnD.

QnD Lesson Two: As the QnD model was being iteratively constructed around the basic ARAMS trout/4-nitrophenol interaction, new ideas for ecosystem management were generated by interacting with the objects and the results of spatial simulations. Both localized and watershed-level management options could be easily created once the basic dynamics were simulated. The spatial modeling of QnD can have both positive and negative influences on system understanding. While stakeholders seek to understand their system spatially, they often manage it non-spatially using more system-wide metrics for success and using spatial simulations to watch for "hot spots" of potential trouble to the greater system.

QnD:HAAF used a more complex object design to integrate a variety of field studies and monitoring data into a modeling/decision framework. Two additional lessons emerged from the development of the initial QnD:HAAF version described below.

QnD Lesson Three: In discussions with a multi-disciplinary scientific team, it was important to use QnD as a common ground to integrate specialized studies into the larger perspective of the team effort. As each specialist added his/her part into the whole, they were able to see their own area and other disciplines represented within the QnD design pictures (such as Figure 8). The QnD development process maintained each participant's attention on the larger problem situation and the objectives of the whole team, rather than the isolation and problem fragmentation that can be created by a specialist view.

QnD Lesson Four: Development of QnD:HAAF showed the dangers of spiraling into greater and greater complexity to capture elusive or obscure ecosystem traits. An important object design principle is to avoid being drawn into a "complexity trap" with ever-increasing complexity in the model engine. While the structure of QnD allows almost endless detail in constructing components, processes and data, developers should remember that QnD first stood for "Quick 'n Dirty" and should be seen as a useful sketch of the ecosystem and its management/social context. Object designs should be as simple as is practical to capture ecosystem performance. Greater complexity almost always means less transparency of the engine mechanisms.

These lessons described are mostly anecdotal and were noted from the various interactions between QnD developers and stakeholder groups. The QnD model is designed to be quickly changed to add new parts and entire simulation concepts and further code development continues to allow it to be relevant to integration-style research and decision-making. While QnD is not supposed to be an exact predictor of future events, it can be a useful "cartoon" of a system-wide environmental and social system interactions. In this definition, a cartoon aids the reader understand a few of the more salient system features while still appreciating the complexity of the challenge. A fundamental aspect to taming the wicked environmental challenges ahead lie with the correct mixture of people (stakeholders), processes (decision methodologies) and tools (models of various complexity) for the understanding a few fundamental system elements and an appreciation of the complexity that surrounds the management choices.

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