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QND: A SCENARIO-BASED GAMING SYSTEM FOR MODELING ENVIRONMENTAL PROCESSES AND MANAGEMENT DECISIONS

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Abstract

In this chapter, we introduce a generic environmental modeling system that has been developed using an object-oriented approach. The Questions and Decisions™ (QnD™) model system combines both number-based calculations with value-style judgments. It can integrate ideas and data that are well-studied with concepts that are estimated from expert knowledge and experience. A specific QnD version is constructed through conversations with stake-holders and decision-makers. The wishes of the stakeholders are created through configurable objects designed to be quickly made and quickly altered through subsequent learning and iteration.

QnD-simulated ecosystems are represented by combinations of component, process and data objects that are constructed through the use of XML-based, input files. This design allows different ecosystem/habitat/organism/chemical combinations to be efficiently formed, simulated and documented. The flexibility of the model is demonstrated through its non-spatial application to a terrestrial ecosystem (Kruger National Park, South Africa) and a spatial risk assessment application within an idealized US river system (as a demonstration for the US Army Corps of Engineers). Unlike traditional decision support systems that direct outputs at a discipline-specific management, the model has been created as a game to stimulate discussions and analysis among managers, scientists and stakeholders who are working increasingly closely within an adaptive management context.

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1. Introduction

Ecosystems exist within matrices of human landscapes. These ecosystems have value (Costanza *et al.*, 1997) and must be managed appropriately in order to sustain the benefits they provide. The growing problem is that the scale at which human activities are occurring is approaching the scale at which ecosystem dynamics occur (ONeill *et al.*, 1998), such that ecological processes and economic activity can become part of the same dynamic system. Consequently, ecosystems become less resilient to exploitation and the appropriate management of these systems becomes increasingly complex, especially with differing human values and expectations of the system. The interplay of various social, technical and environmental forces at differing time and spatial scales has been termed "*Panarchy*" (Gunderson *et al.*, 1995; Gunderson and Holling, 2002). Attempts to integrate the various social-, technical- or ecological-based solutions often highlight one viewpoint while shortchanging the others (Gunderson and Holling, 2002).

Interdisciplinary collaboration is the key to resolving natural resource problems of the 21st century (Holling, 1999; O'Neill *et al.*, 1998), within which greater sharing and collaboration between scientists is implicit as a way of achieving "bigger" science (Houlahan, 1998) to better manage ecosystems. This does not necessarily mean "large-scale science" (Walters, 1997), nor does it mean that results from small-scale experiments can be scaled up without a clear understanding of scaling rules (Rastetter *et al.*, 1992). We feel that large-scale science should not be an endpoint in itself; but that interdisciplinary research should seek the appropriate scale of the problem, where the scales of observation and management match the scale at which the problem is occurring (Jewitt and Görgens, 2000a).

"The goal of conservation management is shifting from managing species for their intrinsic value, to managing them for their interactive roles in ecosystem functioning…" (Rogers, 1997). Management of natural resources occurs under uncertainty, but the use of resources and the need for management will continue (Johnson, 1999a). The management challenge is to gain insight into change in complex natural systems. One approach is known as strategic adaptive management, and is based on a concept of managing natural systems through a process of careful testing rather than trial and error (Walters, 1997). Institutional barriers and inertia pose the greatest threat to the successful implementation of adaptive management (Walters, 1997; Walters *et al.*, 2000). Additional problems include too much focus on the models while ignoring the problems, scale linkages between different models (Walters, 1997; Jewitt and Görgens, 2000b), and the definition of appropriate goals (Johnson, 1999b).

Often management decisions must be made in the absence of adequate data, which is where modeling becomes a useful management tool. Thus a model's development should be driven by the objectives of the management program, rather than the available data (Starfield & Bleloch 1991). "In a decision-making context, the ultimate test of a model is not how accurate or truthful it is, but only whether one is likely to make a better decision with it than without it" (Starfield 1997). Scenario modeling is a useful tool for envisaging future situations in an unknown future (Breen, 1998). Models help to expose gaps in data and understanding, and help to screen policy options, especially under conditions where time is limited and systems are sensitive (Walters *et al.*, 2000).

In this chapter, we introduce a generic environmental modeling system that has been developed using an object-oriented approach. The flexibility of the model is demonstrated through its non-spatial application to a terrestrial ecosystem (Kruger National Park, South Africa) and a spatial application within a generalized river system (as a demonstration for the US Army Corps of Engineers). Unlike traditional decision support systems that direct outputs at a discipline-specific management, the model has been created as a game to stimulate discussions between managers, scientists and stakeholders who are working increasingly closely within an adaptive management framework (Rogers, 1997).

2. Problem Statement and Objectives

Natural systems are complex webs of synergies with species interactions providing a reflection of fast and slow processes (Vannote *et al*., 1980; Frissel *et al.*, 1986). A question that often arises is "how do we understand seemingly random or stochastic patterns, and how do we manage so that system variability is maintained?"

Typically, ecologists have adopted a reductionist approach to understanding ecosystems. There is a quest for the ecological "Holy Grail" – a set of mathematical equations that explain system behavior, which are obtained by breaking systems down to their basic units. Certainly there is merit in this idea. For example, (Stone, 1996) provide numerous examples where apparently random oscillations can be explained by deterministic chaos, where a small number of equations can model a system precisely. While this approach may be the most manageable one, it ignores the idea that through synergies, the sum of the individual parts is greater than the whole. Consequently, deterministic equations are not able to adequately explain system behavior. Very often neither the data nor the ability to represent natural processes as equations exists (Matsinos *et al.*, 1994). Furthermore, natural systems do not seek equilibrium through successions, but rather exist in a state of non-equilibrium where disturbance is important.

The use of simple, pragmatic models that require relatively fewer parameters than complex models is useful in ecological studies (Jeppesen and Iversen, 1987). This approach was useful in highlighting certain management issues within the Colorado ecosystem (Walters, 2000), where a suit of small models at multiple scales of time and space were used to assist scientists and managers. Our approach is to make use of simple "rules" and relationships to model complex systems; simple game models are an effective way of exploring this complexity. The interaction of simple sets of rules are able to create dynamic "systems", such as John Conway's "Game of Life" (Green, 1998), and complex patterns if we view natural objects as simple computers with their own sets of rules (i.e. cellular automata) (Green, 1998). This approach can be applied at the landscape level if the landscape is seen as a collection of cells. These ideas can in turn form a useful basis for more complex models that are designed to promote management. However, bringing together different models at different scales is a daunting task, and involves finding common units, such as fish habitats (biotic models) and geomorphological units (abiotic models) (Jewitt *et al.*, 2000).

The idea of management as a "game" involving different roleplayers, can reveal important general patterns of system behavior, as illustrated by the "Nonpoint" model developed by Carpenter *et al.* (1999). This is essentially a simple system with few roleplayers, and 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 system. Starfield (1993) presented a frame-based modeling approach, which consists of collections of smaller models representing different states (frames) within a single system. Different frames were invoked according to certain sets of conditions and rules. Frame-based models could be made more powerful to 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).

While models have been successfully used for both early systems understanding and facilitation and for later system optimization, we believe there is a significant need for a quickly configurable, spatial model to efficiently represent both formal and informal knowledge into an iterative, interactive format for further management exploration. This model would take initial ecosystem understanding and allow scenarios to be played out to both further refine ecosystem understanding as well as sketch out potential management responses for further, systematic exploration. This model would operate efficiently in between simplified systems understanding models and more complex numerical/optimization approaches by adopting elements of each approach and being very adaptable to either stakeholder goals/preferences or scientific understanding.

This chapter has the following objectives:

- Introduce the design and structure of the Questions and Decisions™ (QnD™) model system;
- Demonstrate the use of the QnD model for adaptive management scenarios in two different ecosystems with multiple drivers and stressors;
- Highlight the lessons learned and next steps for the modeling system.

This chapter is divided into four sections. The first section introduces the QnD model, its design and construction. The second section describes the strategy of developing and using QnD with various stakeholders and scientists in addressing environmental challenges. The third section shows two QnD applications in ecosystem management while the forth section highlights the overall lessons learned from QnD applications.

3. QnD: an object-oriented management "game"

QnD is an acronym for "Questions and Decisions", or alternatively "Quick 'n Dirty", as both of these phrases emphasize the ideas we incorporated into the model from the outset: that our model would not only be appropriate to general environmental

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management problems for specific areas, but also that the model would be generic enough to be readily convertible between different ecosystems with different sets of drivers and problems. However, it is important to understand the modeling context of the QnD model before further details of the model itself are given.

Object-oriented models have been increasingly used to model ecological systems at various scales (for example, Matsinos *et al.*, 1994; Mooij and Boersma, 1996; Railsback *et al.*, 1999; Railsback, 2001; Railsback and Harvey, 2001; Sekine *et al.*, 1996). The object-oriented modeling approach is useful in modeling natural systems, since the "attributes of inheritance, polymorphism, data protection and modularity, provides a natural framework for simulating real-world phenomena involving individual organisms" (Matsinos *et al.*, 1994). Mooij and Boersma (1996) found that "the object-oriented programming paradigm is well suited for the creation of simulation models of ecological systems". Objects (fish, elephant, habitat) interact with each other according to sets of procedures and rules. An object-oriented modelling approach has the advantages that each model object falls within a hierarchy of other objects, so that inheritance relationships avoid unnecessary coding (Mooij and Boersma, 1996). Objects lower down the hierarchy inherit all the attributes of the objects higher up the hierarchy (Budd, 1991; Silvert, 1993). This approach means that it is considerably easier to add new objects to a model, and redundancy in programming code is minimized (Silvert, 1993). The Object-Oriented Programming (OOP) approach means that one can develop models that are simpler and closer to natural ecosystem structure than with procedural languages; it is also possible to modify and refine these models more efficiently. Ecological processes can be modelled at different scales within the same model, depending on the purpose of the model (Matsinos *et al.*, 1994; Mooij and Boersma, 1996). By using rules within an OOP, animals are able to interact with their habitat and with other animals (Mueller, 1991). Animal objects are assigned characteristics and behaviours; the animal objects live within habitat objects that carry relevant information such as vegetation and soil type (Mueller, 1991).

Fishwick (1995) describes the ATLSS (Across-Trophic-Level System Simulation) modeling system for the Florida Everglades. This was a collection of different models at different scales, depending on the trophic level being studied. For example, individual-based models were used for higher-trophic organisms, while general population models were used for organisms from lower trophic levels. Collectively, the models formed a "multimodel" (Fishwick, 1995) to provide a landscape-scale ecosystem model.

In designing the QnD model, we have developed an intermediate-scale management "game" model that draws on many of the ideas described in the previous section. The aim is to present the model as a game which involves both managers and scientists. Such a modeling system will add to the existing abiotic-biotic models already developed for wildlife areas such as the Kruger National Park, South Africa (Weeks *et al.*, 1999; Mackenzie *et al.*, 2000). The model links abiotic drivers to biotic responses using simple rules and cause-and-effect relationships. The object-oriented framework of the QnD model provides flexibility in the code, where additional objects and methods can be added with ease. Thus our model was developed with the following principles in mind:

- **One design, many ecosystems**: to provide a generic object-oriented modeling framework that can be adapted for different ecological systems;
- **Single and double loop learning**: to provide adaptive management support by scenario playing to view tactical, strategic and system-wide issues;
- **Ecology meets engineering**: to allow complex ecological situations to be constructed from relatively simple model designs;
- **Right problem, right scale**: to incorporate a degree of scalability (small and big time steps in both spatial and temporal scales);
- **Ecosystems *have value and are valued:*** to some broadly definable extent (the concept of existence value and political issues/popularity should be taken into consideration);
- **Precise and vague, together**: to allow within the same ecosystem, some things may be known or valued at precise levels while other nearby things may be vaguely known or valued. These two aspects must be included and embraced within an iterative framework;
- **Fast development and continued iteration**: to allow interested people to quickly set up model simulations and just as easily change them when further learning occurs.

The entire QnD system is coded in the Java language and is a combination of original code and open source libraries/application programming interfaces (API's). The QnD system is divided into two parts: the *Simulation Engine* and the *Game View* as shown in Figure 1. Each part has a primary objective to either ***create information*** or to ***communicate information*** to the users. The Simulation Engine works to synthesize the various data and systems concepts into useful constructs that can provide systematic calculations and information in a modular and quickly-altered platform. The Game View allows users to see the system in more graphical (less number-based) methods and to implement management options in a simplified way.

3.1 QND MODEL DESIGN: THE "GAME VIEW"

The Game View constitutes what a "player" sees and reacts to with the various management options in the player's world. Each game view is made of a map viewer (GeoToolsLite API), scrolling time series charts (Chart2D API), warning lights and management selection widgets.

The game view has several types of outputs that can be configured by the user via XML (e**X**tensible **M**arkup **L**anguage) file inputs. By presenting the outputs in a selectable form, the QnD system allows users to choose how they want to see their output, including the following output options as described in Figure 2 and listed below:

- Geographic Information System (GIS) maps that are updated on each simulated time step;
- Mouse-activated charts and text for individual spatial areas (pie charts and text line descriptions);
- Warning lights that change at user-selected critical levels;

- Scrolling time-series charts (listed on user-defined, tabbed pages);
- User-defined, text output files in comma separated format.

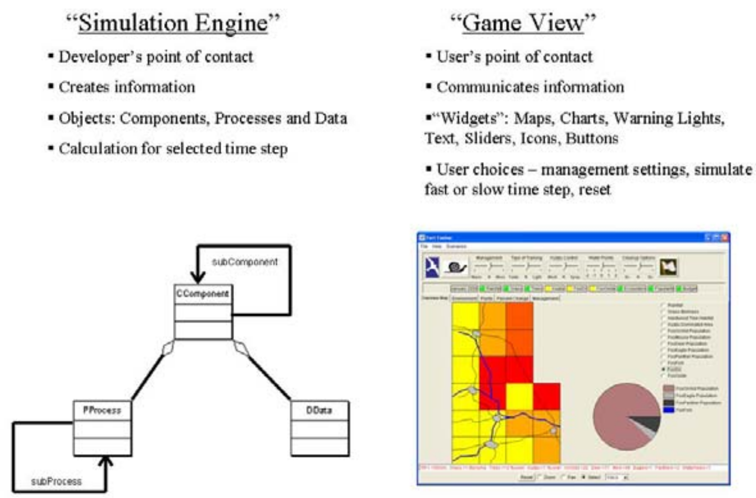

Figure 1. QnD model main parts: simulation engine and game view.

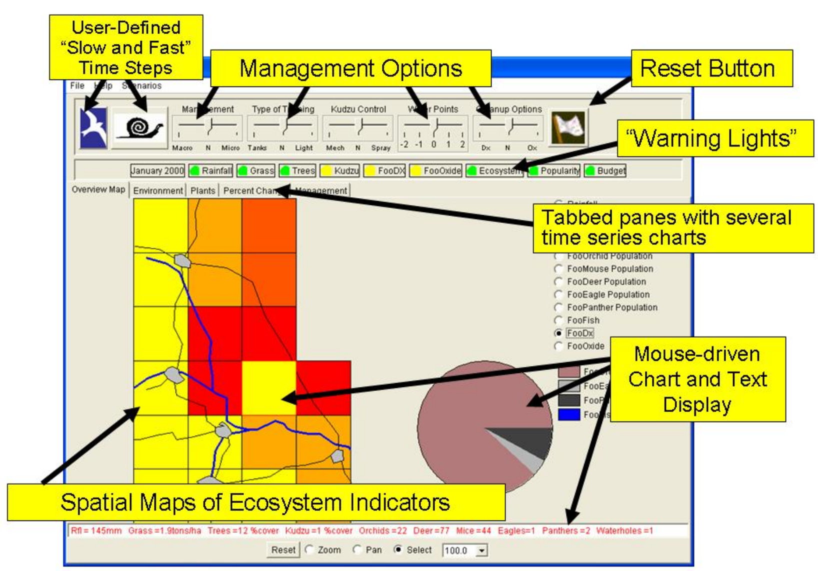

Figure 2. QnD game view features.

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3.2 QND MODEL DESIGN: THE "SIMULATION ENGINE"

The QnD simulation engine 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 *"An elephant will trample two trees per day."* could be interpreted as the Components (**C**Elephant and **C**Tree) with a Process ("**P**Trample") and Data (**D**ElephantPopulation and **D**TreePopulation). In this case, the Process "**P**Trample" would use the **D**ElephantPopulation to calculate the reduction in the **D**TreePopulation (by 2 x **D**ElephantPopulation).

3.2.1 QnD Component Objects

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 can be 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.

3.2.2 QnD Data Objects

DData objects store all the relevant information for a simulation. All DData objects are created in the input files and represent a composite variable as seen in Figure 4. Each DData has several attribute variables that allow for various calculations. All attributes are not used for each DData as some data object definitions may use other attribute features while others do not. For example, a DData object that is linked with a time series file (through its DriverLink attribute) may constantly change current values over time while another may represent a static variable in the simulation and may not use any other attributes besides current value.

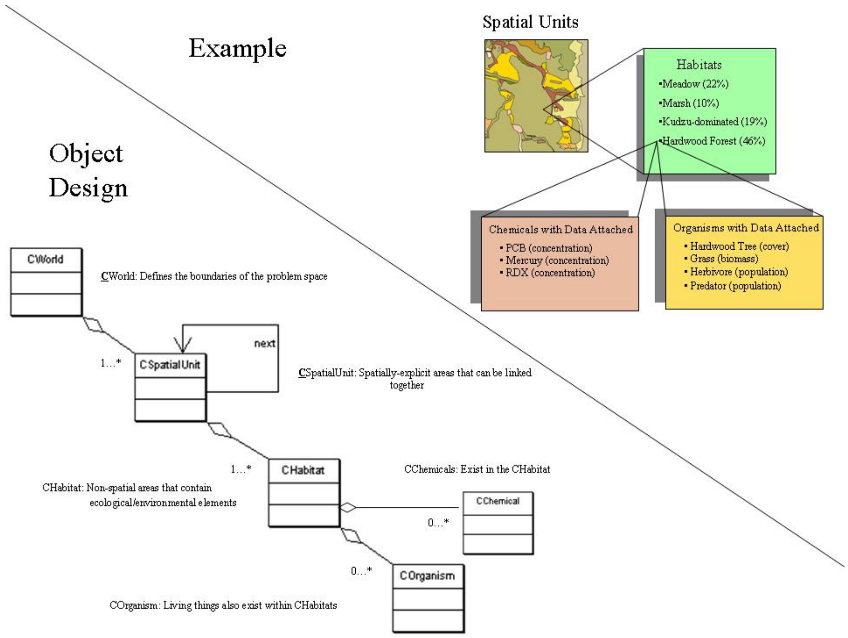

Figure 3. QnD component design and example.

3.2.3 QnD Process Objects

Processes provide the action within QnD. Process objects use DData objects as inputs, provide a calculation or series of calculations and then write the resulting products into output DData objects. Processes can used individually as described in Figure 5. In addition, processes can be designed with constituent sub-processes within them to create a series of processes for more complex interactions, as described in Figure 6. Table 1 shows the different types of processes currently available in QnD. The example in Figure 6 shows how sub-processes can be linked with interactions between DData objects and two processes. The current values of DGrassBiomass and DShrubBiomass are added together with a PAdd process to supply the current value of a DTotalBiomass data object. This same DTotalBiomass current value is the input to a Prelationship object that creates an output that is place into the cumulative effect of a DElephantPopulation data object.

Table 1. PProcess objects for the QnD model.

Process Type	**Purpose**
PAdd	Input1 + Input2 + Input3… + Input_n = Output
PSubtract	Input1 – Input2 - … … - Input_n = Output
PMultiply	Input1 x Input2 x Input3… Input_n = Output
PDivide	Input1 / Input2 / … … Input_n = Output
PTransfer	(Input – TransferAmount) & (Output + TransferAmount)
PRelationship	Two dimensional input/cause (x axis) is used to interpolate an output/effect (y axis) value.
PSimpleLookUpTable	Uses two input data values to choose another output value from user-defined table

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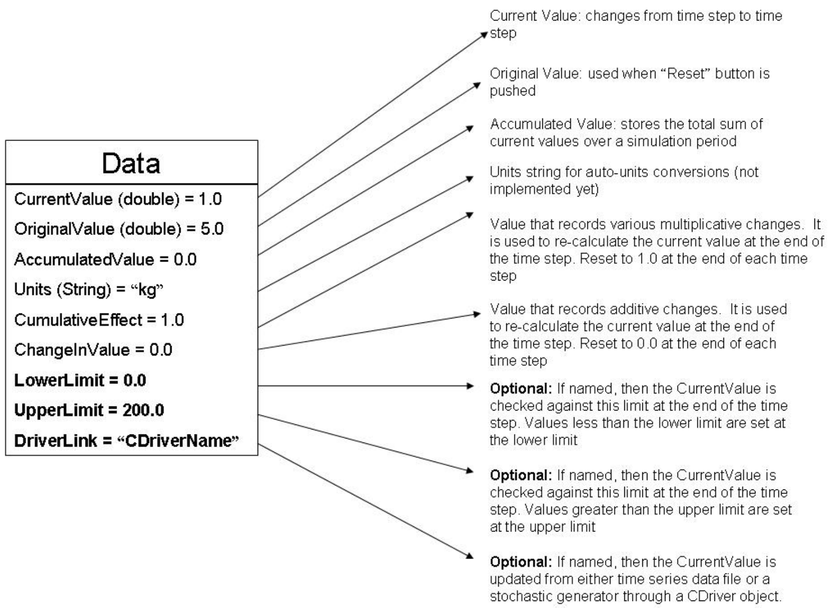

Figure 4. Data object design and attribute descriptions.

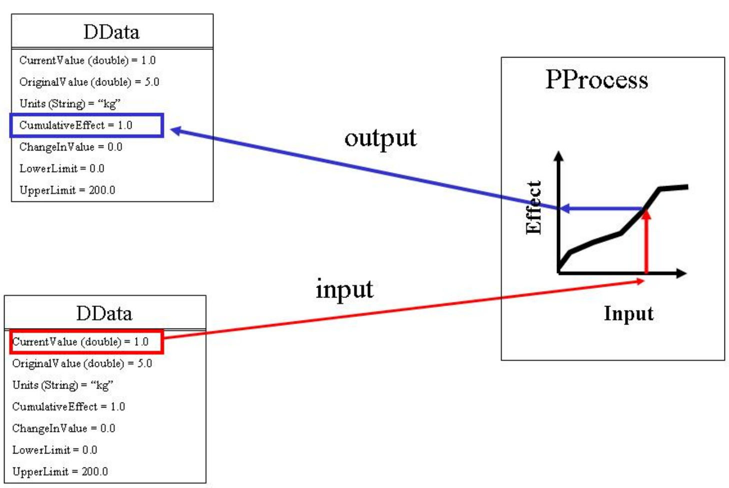

Figure 5. Example PRelationship process object.

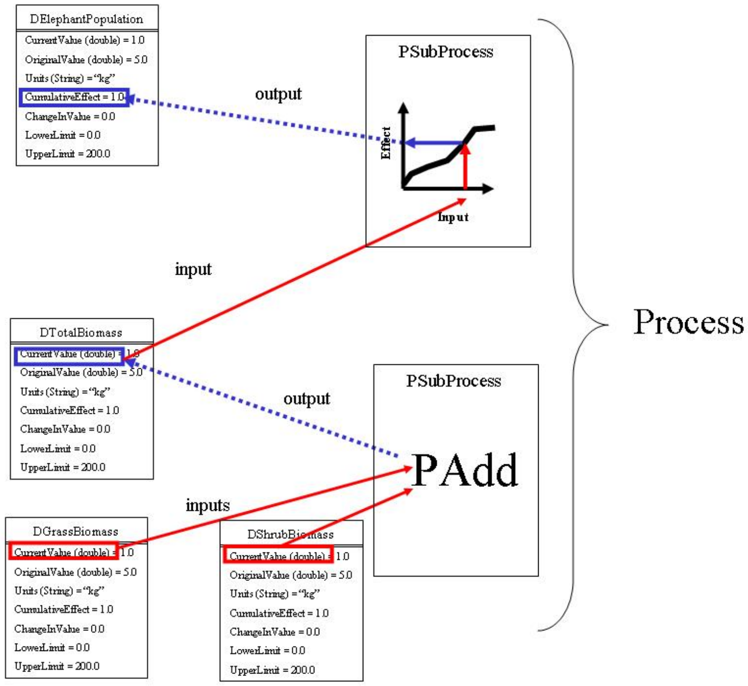

Figure 6. Process objects can be created with multiple "sub-process" objects to form more complex calculations.

3.3 ASSEMBLING QND OBJECTS

Each version of QnD is created entirely from the XML file inputs. Figure 7 shows the seven input files and their use to create the QnD Simulation Engine and Game View. The QnDStartHere file is read by QnD to find the input and output file paths as well as the exact filenames of the other XML files. The QnDWorld file is read to construct the various spatial units along their constituent habitat, organism and chemical objects. Any DData objects that represent spatially unique properties such as local concentrations or population levels are included in the QnDWorld file. The QnDTopology file is used to link various spatial units with each other. The QnDOrganism and QnDChemical files are used to create DData and PProcess objects that all occur in all instances. The QnDOutput.xml file is read to create user-defined files of DData values in a comma separated text format.

The QnDManagement file is used to define the various parts of the game view including the map layers and user-selected maps, scrolling time series charts, warning lights and management options. In addition, certain simulation engine components such as scenarios along with their time series files or stochastic generation settings are set in this file.

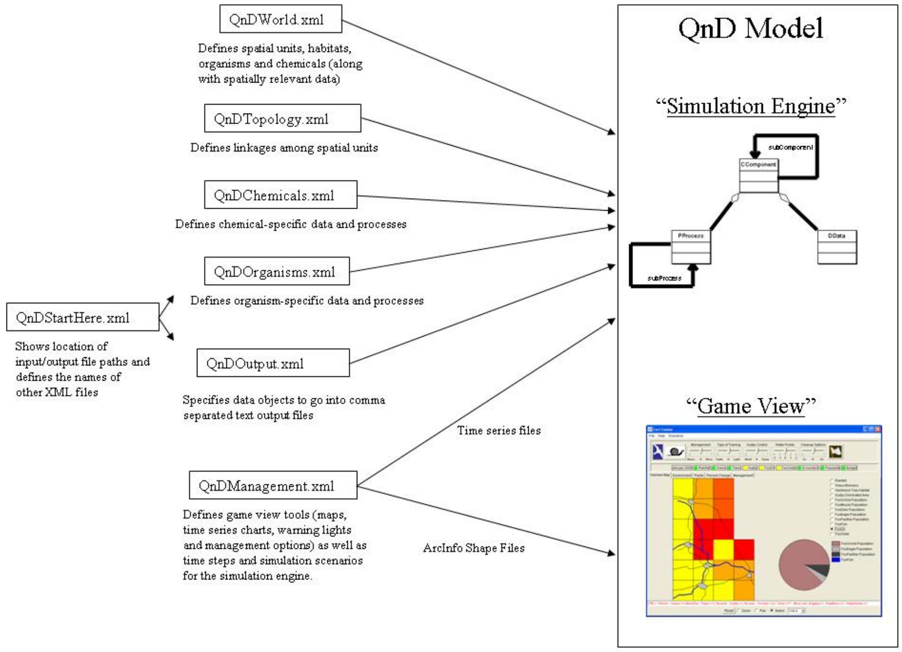

Figure 7. QnD input files are used to generate both the simulation engine and the game view.

After all input files have been read and the objects instantiated, the QnD system waits for user input including the following options:

- Look over the simulation information
    - Switch Map View (with radio buttons)
    - Switch Chart View (with tabbed pages)
    - Review specific spatial unit data values (by pointing with the mouse)
- Set some management options by interacting with the map and setting management sliders
- Simulate a short or long-term time step
- Restart the simulation to its initial settings by pressing the clicking on the reset (white flag) icon.

3.4 PEOPLE AND QND

There are 3 stereotypical groups of people (or actors) involved in QnD simulations, as shown in Figure 8. These three example groups are named *players*, *developers* and *coders*. Players interact mostly with the Game View while playing and exploring the ecosystem, potential management responses and trade-offs. Many players are stakeholders but can be anyone who has an overall interest in the system. They see the simulated world as a larger, integrated ecosystem and have broad, varying interests.

While players may have some interest in certain areas of the QnD Simulation Engine, they mostly have interact with the Game View, the management options, functional information and QnD operation that approaches some level of reality as they understand it. In this fashion, players provide an important reality check to the overall design and function of the QnD system.

We divided the traditional model/code developer role into two separate roles (*developer* and *coder*) to include specialists that are not well-versed in computer science and formalized modelling to functionally interact with the QnD system. *Developers* design and implement the game view and simulation engine objects using the XML input files. While a developer might be a player as well, their primary role is to translate the broader ideas of the players into functional object designs that are represented in the input files. Another fundamental role of developers is to provide any formalized calibration or validation of the simulation engine/game view that is desired by the players. This confidence building aspect is an important function in building trust and interest into any simulation results that are seen by the overall group as critical.

While developers may have interest and/or access to QnD java source code, they should not be spending much time altering source code to achieve their modeling objectives. This role is assigned to smaller, more technical group of *coders*. Coders interact mostly with the java source code and concern themselves with the overall applicability and expansion of the game view and simulation engine parts as well as the functional deployment of the QnD models. Coders have control and responsibility of the overall design and evolution of the QnD system for all groups of players and developers. Coders may take specialized suggestions from players and developers and implement them at a broader more abstract level within the source code to take advantage of new developments in the Java language, computer science concepts or internet technologies.

4.0 QnD: Development and Gaming Strategy

The QnD model has been developed as a useful tool embedded in a larger process of stakeholder and public participation when utilized to generate questions and decisions for complex environmental management. 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) as a way to view a complex environmental problem situation from a variety of technical, social and cultural perspectives. This section reviews the theory and practice that contextualizes the development of a QnD model.

4.1 QND: MODELING AS LEARNING

The QnD development process is typically embedded in a context of environmental management where information is uncertain and decisions regarding improvement need

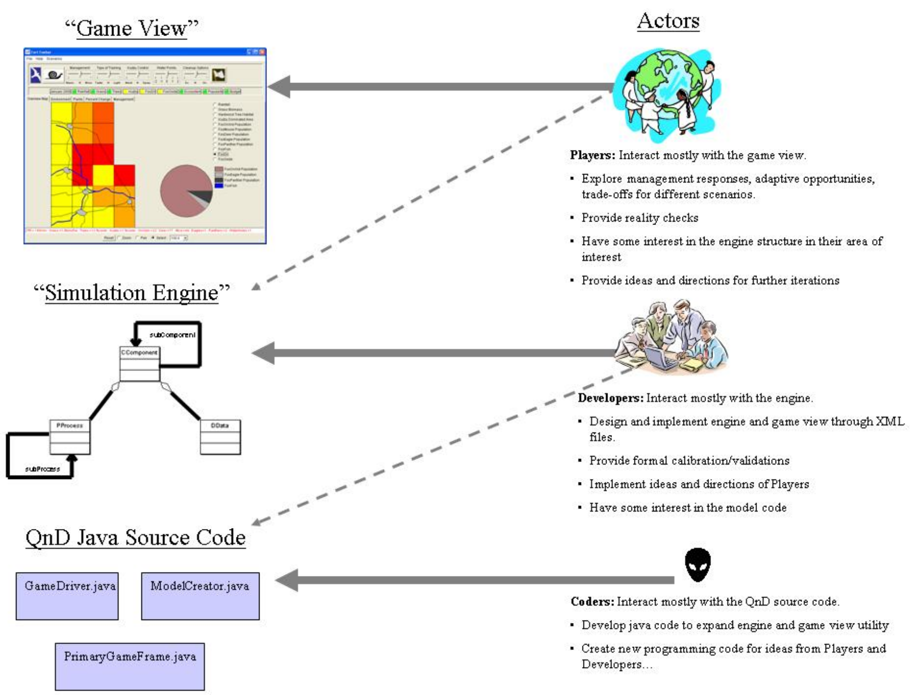

Figure 8. Diverse groups of people will interact the QnD system in different areas.

to be made. Collaborative building of a QnD model creates a critical dialogue amongst stakeholders, simultaneously gathering the technical data that is available and also clarifying values and beliefs about the environmental system. The modeling development process as a learning process is based on a soft systems understanding of problem exploration and problem understanding.

Traditional problem solving approaches based on a mechanistic and reductionistic view of the world have shown their inadequacy in the face of the vast scale of modern problems. Capra (1996) suggests that major problems cannot be understood in isolation, but instead must be viewed in terms of interconnectivity and interdependence. He calls for not just a holistic way of viewing problems, but an "ecological" mindset that recognizes how each aspect of a problem is imbedded in a natural and social environment. Checkland (1976, 1981, 1999), whose primary concern is with the social world, makes a similar observation when he suggests that integration, rather than further fragmentation, is needed to think about complex problem situations. He argues that scientific inquiry can be described as a particular kind of "learning system." To this end, the QnD model can be utilized to assist dialogue and learning within a problem situation.

Soft systems methodologies are essentially learning models, and can be related to Kolb's cognitive/action cycle (Kolb, 1984) representing four different knowledge forms: diverging (what is there?), assimilating (what can we do?), converging (what is important?), and accommodating (what does it mean?). Figure 9 shows soft systems considerations in terms of Kolb's knowledge forms (after Bawden *et al.*, 1984). The QnD model can be used as a facilitative device to take participants iteratively through the four stages of the learning cycle. The model presented as a game generates discussion amongst the stakeholders about their understanding of the problem situation and provides an interactive way of testing and debating a variety of actions that could be taken to improve the situation. Instead of talking about the implication of various actions in the abstract, the QnD game allows participants to try out different management alternatives and investigate possible repercussions of those decisions. Additionally, the game can be structured around different scenarios from different perspectives, allowing participants to test their assumptions within different future worlds, thus revealing the biases in differing perspectives. QnD has been designed to be used within more formalized scenario generation processes, such as the planning approach developed at Royal Dutch/Shell (van der Heijden, 1999).

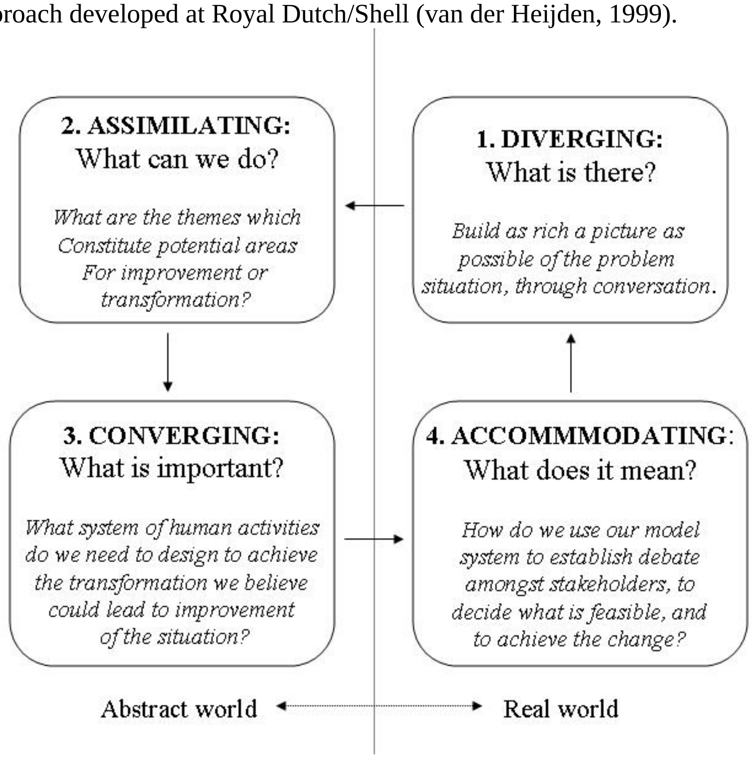

Figure 9. Soft systems considerations represented in terms of Kolb's Knowledge Forms (after Bawden *et al.*, 1984).

The notion of modelling as learning differentiates itself from a traditional scientific hypothesis-testing approach which seeks to establish a firm problem definition early on in the research process. Using Kolb's terms presented above, this traditional approach rushes past diverging and assimilating in an attempt to converge on a definition of the problem as early as possible, in order that research may begin and solutions may be found. One disadvantage of this early convergence is that formalizing the problem definition too soon in the planning process can establish a faulty foundation with a biased starting point; as a result, the solutions that are generated are solutions to the "wrong" problem. If the problem is defined without a full consideration of all possible opinions, then the solution will be off target. Churchman (1979) recommends a process of "sweeping in" pros and cons, friends and enemies in order to reveal the range of possible assumptions about the problem situation and what would constitute improvement. Using QnD in the early stages of a decision making process enables participants to "sweep in" this bigger picture through debating the problem situation, building the model, and playing the game. Divergence is an uncomfortable process, as those who are schooled in a scientific way of thought desire to formalize the problem mess as soon as possible. The QnD model development process is a tangible way to help participants make sense of this mess as they learn more about the many possible perspectives and dynamics in the problem situation, equipping them to make decisions, and to continue exploring possible actions that may improve the situation.

Model development traditionally forces the problem situation into a structured form, and in the process loses important features of the situation, such as the human component. Most technical models in the past have been built around mathematical equations which give the impression of precision and reliability in an attempt to find the one best way to solve problems. This deterministic use of models and computer technology has created suspicion in the general public who were not convinced that the computer could process the data and print out a neat and tidy solution for their messy problem situation. The general public could see through the enthusiastic use of technology, recognizing that the model was often working on the "wrong" problem from a mechanistic and reductionist point of view, able to input only quantitative information that is statistically reliable. Many decision makers have realized that the complex problems of today are not only about finding technical solutions, but also about understanding stakeholder experience, knowledge, and values. Because of QnD's design, both qualitative and quantitative information fit side by side. Both hard data, such as field-measured experiments, and soft data, such as experiential learning or general impressions are valid model inputs.

Model development has been used elsewhere as a facilitative device, usually to generate very simple models. One potential limitation of these models is that they are primarily a means for uniting stakeholders around a single systems viewpoint and are less relevant for detailed ecosystem management exploration. QnD is differentiated in that a little more complexity is desired. QnD is not created in a one-time meeting. Instead, participants interact at least two times within a QnD learning process as shown graphically in Figure 10. The first meeting is an initial "genesis" session to elicit the key features of concern in the problem situation from potential players. Then developers build an initial game, returning one to two weeks later to play the game with participants and to test scenarios. After playing the game, revisions to the model can be made, and the game played and revised repeatedly as needed during the decision making process.

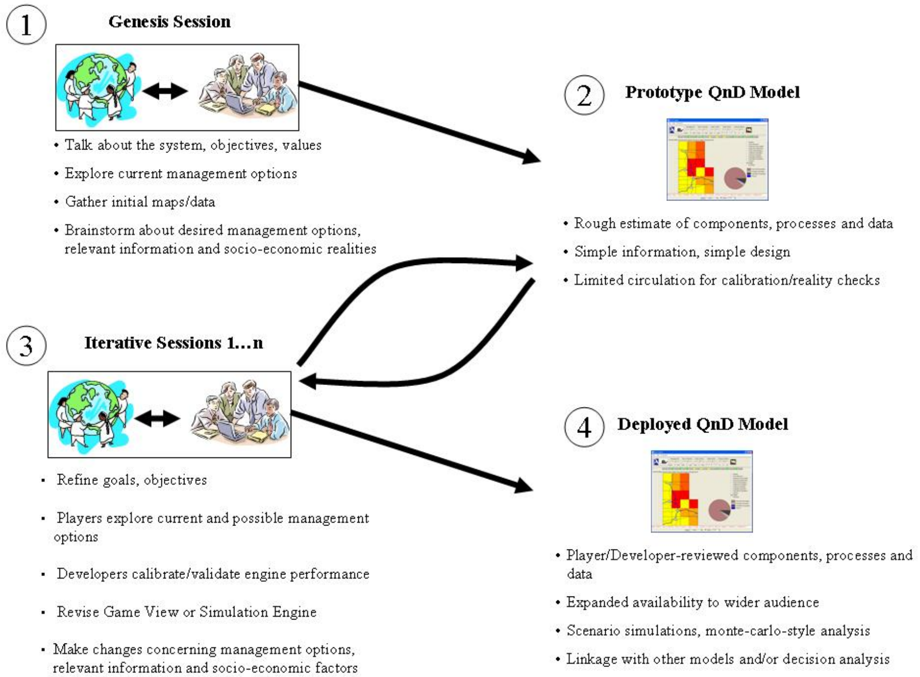

Figure 10. QnD development is iterative and allows group learning to be incorporated into the model.

Three primary activities are used to develop a QnD model/game. First, participants describe the problem and its elements 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. Secondly, words and pictures are interpreted into QnD objects. The various system descriptions from the initial meeting 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. The third primary activity takes place during the second meeting with stakeholders when they discuss and debate the problem situation using the QnD model scenarios 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.

5. QnD Case Studies

A good model should be useful to managers while being founded on data and assumptions that can be justified scientifically. While model outputs may approximate the real world situation (*i.e.* there is significant correlation between observed and modeled data), it is important that the mechanisms underlying the model output are the right ones (Snowling and Kramer, 2001). Hereafter, a model only becomes useful to natural resource managers if the model inputs can be coupled with different scenarios, and the outputs compared against some kind of meaningful threshold.

Management inevitably occurs under situations of imperfect data and incomplete assumptions, but invariably takes the form of "what happens if…?" questions, such as "What will happen to this system if we have a dry season?"; "What happens if a severe flood occurs?", and "What happens if I do nothing?". Thus natural resource managers operate within a spectrum that ranges from "do nothing" to micro-management, which in our model is possible by applying management actions on a cell-by-cell basis, to macro-management, where a blanket management policy is applied to the entire area of interest. Furthermore, it is useful for managers to experience the effects of large and random disturbances that are beyond their control, on the system. This section highlights two applications of the QnD with non-spatial and spatial simulations. Both case studies highlight the QnD development and game/scenario playing process within differing ecological contexts.

Two case studies are briefly summarized in this chapter. We have tried to describe the model structure and function in simplified terms without large detailed object designs or mathematical equations to communicate the basic purpose, behavior and lessons learned from each of these simulations. More specialized, technical documentation is available through a QnD web page (www.risktrace.com).

5.1 QND:NPR - ADAPTIVE MANAGEMENT WITHIN THE NORTHERN PLAINS OF THE KRUGER NATIONAL PARK

The Kruger National Park (KNP) is located in the northeast corner of South Africa, as seen in Figure 11. The park covers a wide variety of climates, ecosystems and soils. Both infertile (deep sandy) and fertile (basalt-based) soils are present and annual precipitation ranges from 400 mm to 750 mm, with high spatial and temporal variability. These varying environments provide a high species diversity in both plants and animals (Joubert, 1986). Rogers (1999) outlined an adaptive management framework that explores the consequences of management decisions by measuring the model outputs against critical thresholds. In the KNP, these are defined as "thresholds of potential concern" or "TPCs". Successful TPCs are based on research that has identified agents of change, and suitable indicators of this change. Systems are variable, and the TPCs for indicators within these systems need to reflect this variability. Furthermore, the TPCs need to be objectively defined and defendable, and exist within an iterative cycle of monitoring (Rogers *et al.*, 1999). The TPCs are not an end in themself, but rather assist in achieving pre-defined management goals, which in turn are constantly reassessed. Part of the goal maintenance system of Rogers and Bestbier (1997) is that the consequences of management actions are examined within the framework of goals. Models become useful to management if they have the capacity for evaluating different scenarios, and testing the consequences of these against objective yardsticks (TPCs). The object-oriented approach of QnD enables managers and modelers to add indicators for agents of change, and measure their response against TPCs under different management scenarios.

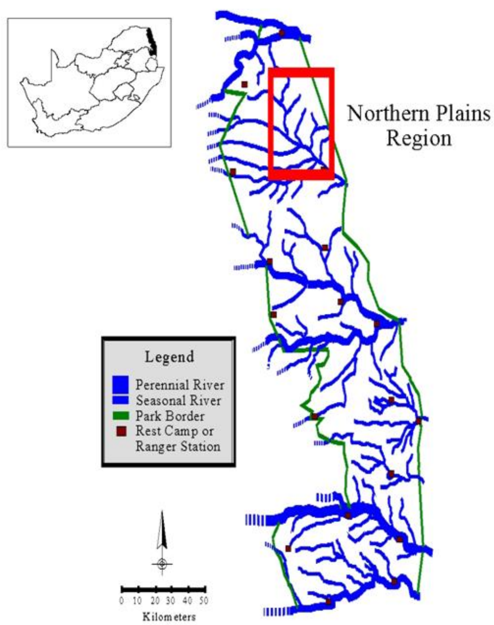

Figure 11. The Northern Plains Region of the Kruger National Park (after Kiker, 1998).

Given the large size of the KNP (approximately 20,000 km^2), a smaller site was chosen to focus the QnD modeling effort into an area of specific interest to both scientists and park managers. The Northern Plains Region (NPR), as shown in Figure 11 is ecologically defined by KNP scientists *Colophospermum Mopane* Shrubveld on Basalt (Gertenbach, 1983) comprises very flat plains of slopes averaging 0.62°. The mean elevation of the NPR is 343 meters above sea level with a standard deviation of 41 meters. The mean annual rainfall varies between 450 and 500 mm per year. The woody vegetation of the NPR is almost completely dominated by dense *Colophospermum mopane* (Mopane) shrub trees with some scattered trees of other species such as *Lonchocarpus capassa*, *combretum imberbe* and *dalbergia melanoxylon*, (Venter *et al.*, 2003).

The NPR has been of interest to KNP scientists and managers because of its role in supporting rare antelope species including roan (*Hippotragus equinas*) and sable (*Hippotragus niger*) antelope, along with Lichtenstein's Hartebeest (*Sigmoceros lichtensteinii*). Declines in those rare species have focussed attention to the NPR's role in maintaining biodiversity within the KNP (Mills et al., 1995; Grant and Van der Walt, 2000; Grant *et al.*, 2002; Grant, 2003). Grant *et al.*, (2002) describe the management goals in terms of a command and control-style paradigm and the emergence of a newer adaptive management paradigm using the resilience concepts found in Gunderson and Holling (1995). More interventionist management was used in the form of water provision, burning and elephant culling.

Management actions within the Northern Plains occur from a combination of individual expert knowledge and consensus opinion from population and vegetation monitoring data. Historically roan antelope has not responded to various management actions (Grant *et al.*, 2002 citing Pienaar, 1963). Populations had ranged from 150 to 300 since the 1930s. Since the 1960s, KNP management has focused specifically on creating and maintaining viable rare antelope populations. Less suitable habitat was the consensus opinion of the KNP scientists and managers from the early 1960s. The proposed mechanism of the problem was that excess water from the artificial water sources was sustaining in higher populations of zebra for longer periods than their traditional seasonal visit. The combined effects of an extended drought, higher zebra populations and higher associated predators caused a population drop. As a management "experiment", water points were closed in roan habitat and continued assessment and monitoring are continuing. These management experiments were conducted within a highly annual rainfall climate.

The primary purpose of this QnD version was to not to necessarily predict future ecological state variables as much as it was to inform and educate interested parties of the ecosystem management issues within the KNP. Playing the QnD:NPR software allowed non-KNP professionals to test various management responses within an operational framework against simplified TPCs to judge the success within ecosystem, financial and public values.

The long-term objectives of the QnD:NPR game were the following:

- **Ecosystem Viability**: maintain a balance between vegetation, herbivore and carnivore populations
- **Political/Management Success**: maintain a balance between public perceptions and opposition to certain management options (*i.e.* elephant culling)
- **Financial Management Success**: maintain financial reserves under limited budgetary resources

Figures 12 and 13 show the basic structure of the QnD:NPR model. The QnD components, processes and data objects were built from previous model and ecosystem studies (Kiker, 1998: duToit and Biggs; 2003, and O'Connor and Kiker, 2004). Rainfall is the primary driver and varies randomly from 300 to 800 mm/yr. We assume that there is only one large spatial unit with a default bushveld habitat. All species of grass are represented by a simple COrganism Grass with a corresponding data object DBiomass (metric tons/ha). All tree species are represented by a CTree object with a related DPercentCover data object. Animal species such as elephant, roan antelope, zebra and lion are represented by individual objects, each with a corresponding DPopulation data object. No chemical objects were used in this QnD version.

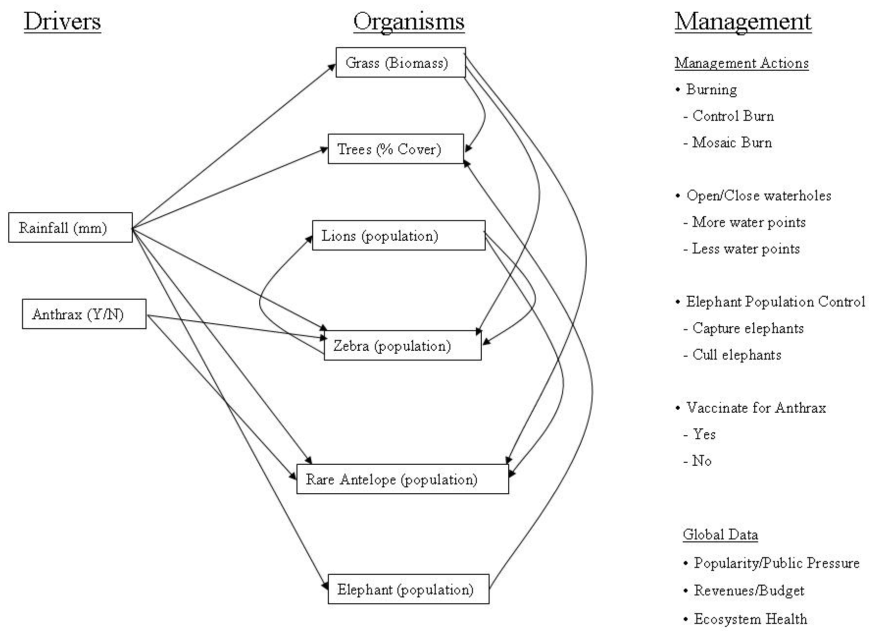

Figure 12. Driver and organism interactions in the QnD:NPR model.

Processes that interlink between organisms are shown in Figure 12. In this version of QnD, all process objects are simple linear relationships in the form:

$$\text{Annual Change in Data Value} = f(\text{Data Value}_1, \text{Data Value}_2, \ldots \text{DataValue}_n)$$

where each f(Data Value) is PRelationship object as described in Table 1 and Figure 5. Multiple effects are combined in a multiplicative fashion. For example, the effect of rainfall upon tree cover may increase the percent cover by 5% while the effects of elephant populations may decrease cover by 8%. These two annual effects would be incorporated as:

$$\text{Tree Cover}_{n+1} = \text{Tree Cover}_n *(1.05) *(0.92)$$

Figure 12 graphically describes the following annual processes:

Grass Biomass (metric tons/ha) = f(rainfall, mm/yr)

Tree Cover change (percent) = f(rainfall, grass biomass, burning policy, elephant population)

Lion Population change = f(zebra population)

Zebra population change = f(rainfall, grass biomass, lion population, anthrax occurrence, number of water points)

Rare antelope population change = f(rainfall, grass biomass, lion population, zebra population, anthrax occurrence, number of water points)

Elephant population change = f(rainfall, elephant population control policy)

Anthrax occurrence is set at a base level of 0.05 probability. For each consecutive dry year (less than 400 mm), the outbreak probability increases by 0.2 up to a maximum probability of 0.95. Any wet year resets the outbreak probability to the base level. If an outbreak occurs on an unvaccinated population, then population reductions of 20% in zebra and 40% in rare antelope populations occur.

Management interactions are described in Figure 13. The following four management actions were explored:

- Water Management: Adding or Closing Water Points
- Elephant Population Management: None, Culling, or Live Capture
- Anthrax Vaccination for Anthrax
- Fire Management: Patch burning, Lightning fires, Plot burning

Management success is related to three primary indices: Ecosystem Health, Available Budget and Management Popularity. These measures were established to give players an appreciation for the issues that ecosystem managers were being judged.

Ecosystem Health change = f(Tree cover, Lion population, Elephant population, Rare antelope, Zebra population, Fire management policy)

Change in Budget = f(Ecosystem Health, Number of elephants captured, Lion population, Anthrax vaccination policy)

Change in Management Rating = f(Ecosystem Health, Lion Population, Elephant Population, Number of elephants culled)

The primary scenario to be explored was random annual rainfall between 300 and 800mm. Outputs were recorded on a single time series graph and included percent change in various herbivore and vegetation species from a baseline starting year of

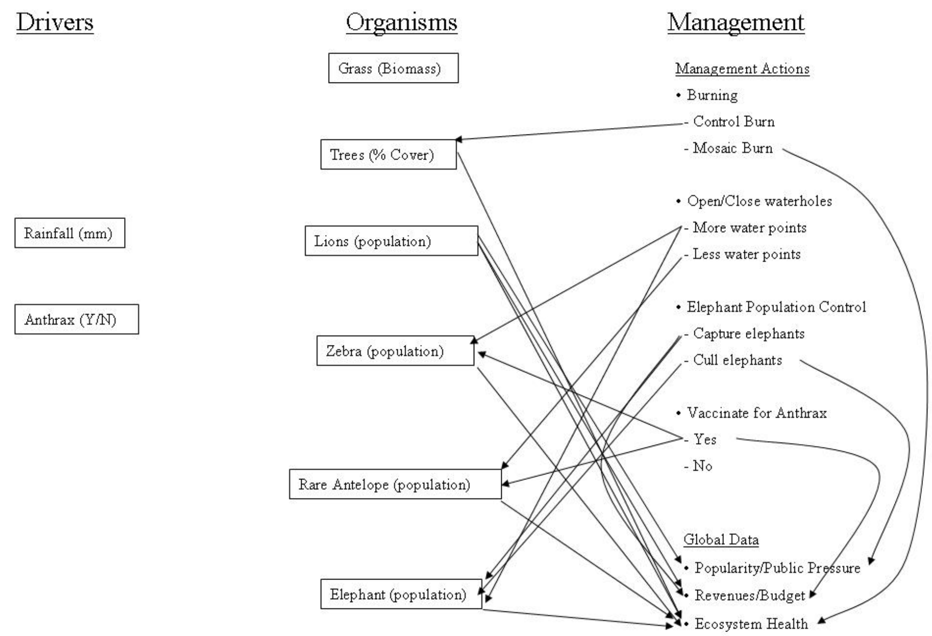

Figure 13. Management-organism interactions in the QnD:NPR model.

2000. Outputs as warning lights included rainfall, grass biomass, anthrax warning level, ecosystem health, management popularity and park revenue. The object of the game was to manage the area for as long as one could before having an ecosystem crash (the ecosystem health level becomes critical), public outcry for a resignation (the management popularity becomes critically low), or park budgets are exhausted (the budget levels become critically low).

This first version of QnD was created to show users the various tradeoffs in ecosystem management and to learn adaptively how to manage an ecosystem with limited resources and options. Simulated ecosystem responses were for the most part accurate to various conditions within the northern plains region. Figure 14 shows a typical QnD:NPR simulation.

Of the various students and interested players who interacted with game, the longest game length was approximately 30 years. This success was due to a combination of good adaptive management and simple luck of having less drought seasons. The general average first response was approximately from 7 to 15 years. Upon restarting the game, almost all players tended to improve their management scores from their first attempt. This occurred even when the players received less favorable climate conditions on the second attempt.

As players played the game, they tended to improve their management skills by learning what interventions worked under what general situations. This adaptive learning went up to a point where then simple "luck of the draw" in what yearly rainfall a player received began to be the determining factor of longer term success.

Over the simulations, several emergent strategies were suggested and debated among players in the scenario:

"Rainfall trumps everything, even elephants" – almost all management was in response to or in expectation of different rainfall levels. Under some scenarios, droughts provided some temporary population control of elephants. Players often would become more skilled at setting up the ecosystem conditions to mitigate small-scale droughts, although droughts longer than 4 consecutive years were often non-recoverable.

"Micro-managing with water?" – given that players could open or close water points with no financial cost, the first choice of action was usually to modify water point numbers. Given the current QnD:NPR structure, this had a larger positive influence on rare antelopes, zebra and elephants, but often led to overpopulation of both species and large population crashes once elephant populations increased over 25 to 50% levels from baseline. Population crashes in rare antelopes were usually instigated by droughts, competition from zebra or anthrax outbreaks.

"Manage elephants early and in smaller numbers" – the social and financial cost of elephant control dictated that frequent control of fewer elephants is less costly (politically and financially) than few large-scale population control actions. In almost all neophyte simulations by players, control of elephants was put-off because of the high cost of the decision. The less politically charged (but financially draining) action of live capture was almost always adopted first with culling as a final, last resort option. In addition, some discussion as to whether the simplistic, linear popularity penalties for elephant culling were accurate to reality as they tended to dominate the use of this option.

"Vaccinate anthrax only when you have to?" – player groups were more mixed over the best strategy for vaccination. Some favored vaccination whenever more than one year of drought occurred while others favored a strategy of building up rare antelope and zebra populations as a buffer against large scale die-offs. This strategy worked in some rainfall scenarios while Figure 14 shows this strategy failing under a combination of an anthrax outbreak and a multi-year drought.

Overall, these strategy discussions were not meant to find an optimal management scheme for the KNP. More realistically, QnD:NPR formed what was jokingly called a "decision sympathy system" (as opposed to the traditional decision support system) to allow non-KNP players to appreciate some of the pressures and limitations faced by KNP managers. The model was quite useful for initiating discussions on basic ecosystem dynamics and whether certain management options would be effective over the long term. Further QnD research and development into more spatialized applications within the KNP are underway.

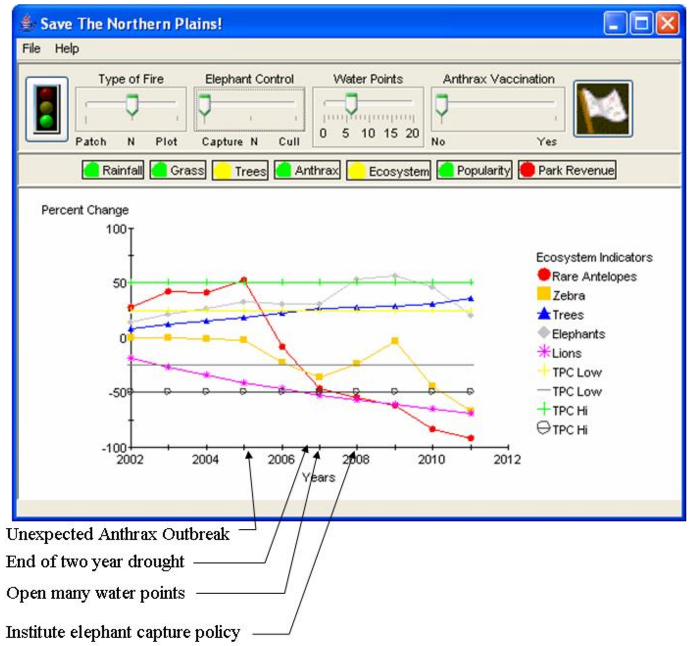

Figure 14. Example QnD:NPR results showing a player's management responses to an unexpected anthrax outbreak and two year drought.

5.2 QND:FOORIVER: INTEGRATING SEDIMENT AND ECOSYSTEM MANAGEMENT FOR MINIMIZING RISK

A riverine ecosystem/dredging/risk version of QnD was developed as a demonstration project for the US Army Corps of Engineers – Engineer Research and Development Center (USACE-ERDC). The FooRiver demonstration was created to show how QnD can be used in a stakeholder setting with problem definition, model design and scenario generation. Functionally, this demonstration version was built from comparative risk assessment concepts and data used in Kane Driscoll *et al.*(2002). A functional management map of the FooRiver system is illustrated in Figure 15. Sections of the FooRiver are divided into 5 river reach management areas (Shaka's Rapids, Petronella Reach, Mandela Straights, Joe's Bend and Bobville stretch) and two reservoirs (FooLockDam1 and FooLockDam2). The FooRiver flows into an estuary as the practical edge of the management area.

Stakeholders in the FooRiver basin have environmental challenges that center around the dredging and disposal of contaminated sediments. FooCB (a fictitious non-metabolized organic, similar to PCBs and Dioxins) is present in river sediments at varying concentrations throughout the FooRiver system. Significant trophic transfer of

FooCB can occur from sediments, through benthic invertebrates and into fish populations. These fish populations are consumed by local recreational anglers.

FooRiver stakeholders have expressed concern over both ecosystem features (abundance levels of benthic invertebrates and fish) and contaminant levels (FooCB levels in fish and subsequent risk to anglers). The primary management options of interest to FooRiver stakeholders are dredging within the river reaches and disposal of the contaminated dredged material. Economic and social concerns are also important for stakeholders in that management budgets are limited and some management choices are more popular than others. In addition, stakeholders have questions about management responses under different climate scenarios including the southern oscillation index ("El Nino", Neutral/Normal, "La Nina") which tend to have different flow and sediment fluxes.

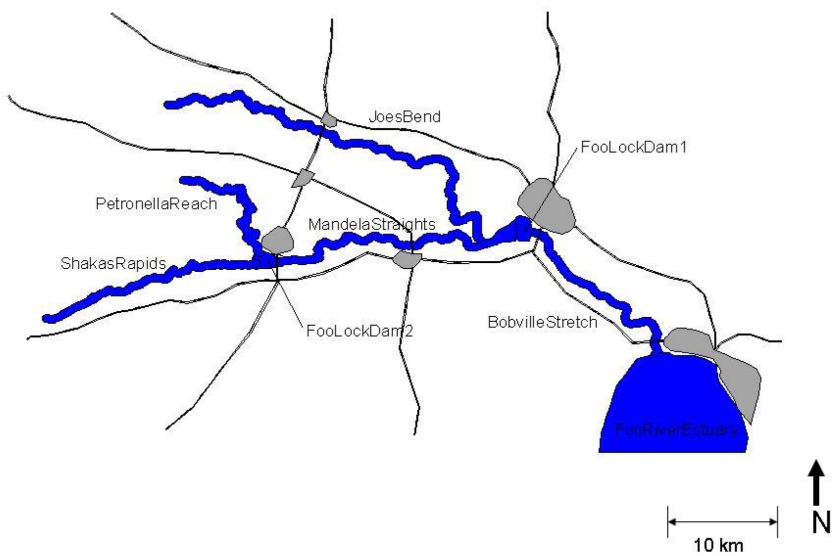

Figure 15. Management map of the FooRiver system.

The primary interactions in each river reach between CDriver, COrganism and CChemical objects are described graphically in Figure 16. Each reach has sediment, water flow and contaminant inputs that are used to determine the flux in sediment FooCB concentration:

$$\text{Change in Sediment FooCB (ppm)} = f(\text{Flow level, Sediment influx, FooCB influx})$$

Kiker, G.A., Rivers-Moore, N.A., Kiker, M.K. and Linkov, I. (2006). QnD: A modeling game system for integrating environmental processes and practical management decisions. (Chapter in Morel, B. Linkov, I., (Eds) "Environmental Security and Environmental Management." Springer, Amsterdam. Pp. 151-186.

Abundance of benthic invertebrates is influenced by simplified logistic growth function and reduced by FooCB concentration and dredging effort.

> Benthic invertebrate abundance change = *f*(current benthic abundance, FooCB concentration, dredge effort)

The FooCB concentration of benthic invertebrates is a derived by a biota-sediment-accumulation factor ($BSAF_{inv}$).

> Benthic invertebrate FooCB concentration = Sediment FooCB concentration x $BSAF_{inv}$

Abundance of fish is positively influenced by simplified logistic growth function and reduced by fish and invertebrate FooCB concentration.

> Fish abundance change = *f*(current fish abundance, current fish FooCB concentration, current fish FooCB concentration)

The FooCB concentration of fish is a derived by a bio-sediment-accumulation factor ($BSAF_{fish}$).

> Fish FooCB concentration = Benthic Invertebrate FooCB concentration x $BSAF_{fish}$

Risk levels in fish consumed by recreational anglers are simulated by a simple step-wise relationship from fish fooCB concentrations

> Human Risk Level = *f*(fish FooCB concentration)

The management-organism-chemical interactions are described in Figure 17. As an initial construct for management, dredging level is described at four levels:

- None
- Low
    - Removes 20% of FooCB from sediments
    - Reduces benthic invertebrate abundance by 10%
    - Reduces total budget resources by 20%
- Medium
    - Removes 40% of FooCB from sediments
    - Reduces benthic invertebrate abundance by 25%
    - Reduces public satisfaction level by 15%
    - Reduces total budget resources by 30%
- High
    - Removes 60% of FooCB from sediments
    - Reduces benthic invertebrate abundance by 80%
    - Reduces public satisfaction level by 35%
    - Reduces total budget resources by 35%

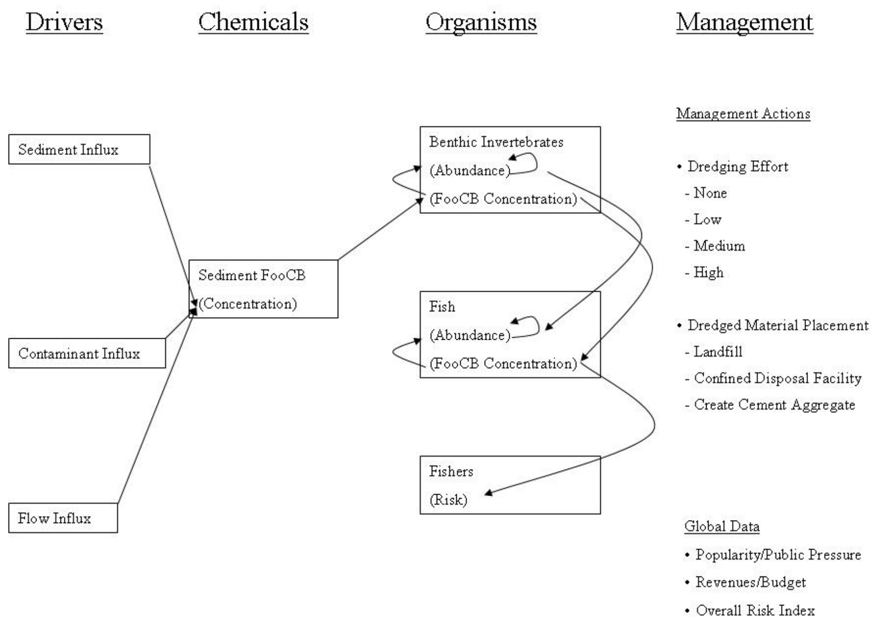

Figure 16. Driver-chemical-organism interactions in the QnD:FooRiver model.

These dredging effects are defined to show both the positive and negative ecosystem effects of dredging as well as the socio-economic cost of implementing different management levels. Once dredging has occurred then the material must be place in one of three potential locations:

- Landfill
  - Reduces total budget resources by 10% per unit dredge effort
  - Reduces public satisfaction level by 5%
- Confined Disposal Facility
  - Reduces total budget resources by 5% per unit dredge effort
  - Reduces public satisfaction level by 20%
- Create Cement Aggregate Material
  - Reduces total budget resources by 15% per unit dredge effort
  - Increases public satisfaction level by 5%

Kiker, G.A., Rivers-Moore, N.A., Kiker, M.K. and Linkov, I. (2006). QnD: A modeling game system for integrating environmental processes and practical management decisions. (Chapter in Morel, B. Linkov, I., (Eds) "Environmental Security and Environmental Management." Springer, Amsterdam. Pp. 151-186.

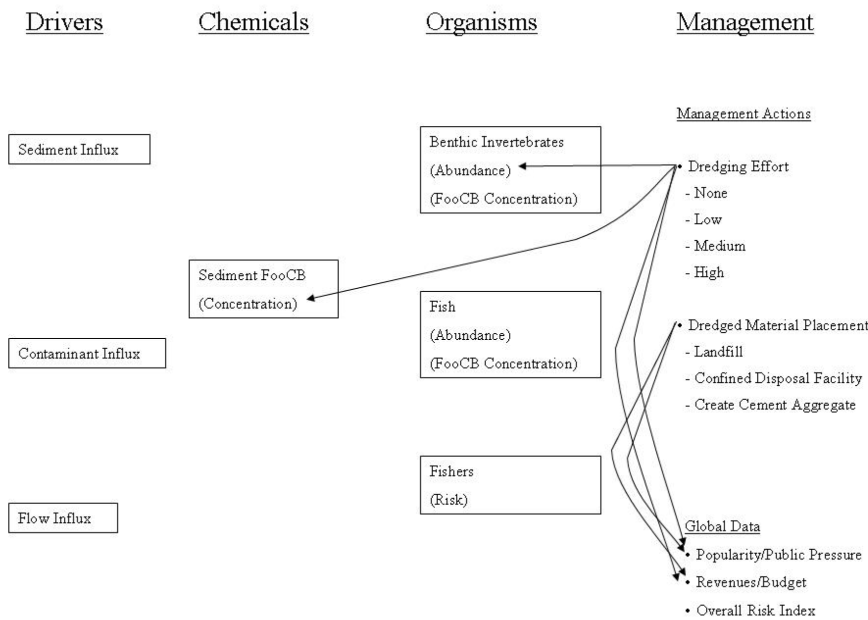

Figure 17. Chemical-organism-management interactions in the QnD:FooRiver model.

This initial demonstration version of QnD:FooRiver was constructed to show the utility of QnD to integrate quite different ecosystem, management and socio-economic data. Figure 18 shows a simulation for one of the upper reaches (Shaka's Rapids) over a fifty year period under three climate scenarios (La Nina, El Nino and Neutral). This reach had a high initial FooCB concentration in its sediments. Figure 18 shows the progression of sediment concentrations, fish abundance and fish concentrations under no-dredging management policies. In the uppermost time series chart, sediment FooCB concentrations decline under Neutral and El Nino scenarios but increase sharply under the La Nina scenario due to its tendency for lower reach flows and sediment loads. The middle time series chart shows fish abundances declining sharply in the Neutral and La Nina scenarios while rebounding in the El Nino scenario. The lowermost time series shows the FooCB concentrations in fish declining in the Neutral and El Nino scenarios while increasing in the La Nina scenario.

Figure 18 shows the dynamics of one management area within eight of the entire river system. The decisions on where and how much to dredge can be quite complex when integrating local complexity (in both time and spatial scales) into a cohesive system-wide management plan. In almost all spatial versions of QnD tested, players find that the addition of separate spatial areas tends to complicate the overall ecosystem understanding and management. Thus, once the spatial concerns are added into the model, it is much harder to formulate adaptive management strategies, especially when social/economic factors are included. The temptation to "deal with hotspots" (either spatial or temporal ones) and ignore all other areas tend to dominate thinking to the detriment of the entire system or in some cases the decisions are to allow some areas to decline substantially while attempting to "save the whole".

In summary of the QnD:FooRiver demonstration, the initial model construct represents the first iteration/round of communication between Developers and Players. All aspects of the FooRiver simulation engine are simplified representations that can be expanded in detail to allow more elaborate calculations of bioaccumulation, abundance, risk or even fish or FooCB movement between reaches. With these simplified processes in hand, players and developers can explore the processes and their interaction with the overall ecosystem response and potential management issues.

6. Discussion/Conclusions

The QnD modeling software and its associated development methodology was created to quickly and efficiently construct a management/stakeholder-relevant model that integrates both explicit scientifically-derived data and expert/anecdotal knowledge. Given QnD's object-oriented design and XML-based input files, systematic iteration with stakeholders is encouraged and promoted. New and novel ideas about the problem and potential solutions can be explored, adopted or discarded to promote greater system learning.

Development of a QnD model is undertaken within a larger context of stakeholder engagement and public participation. When eliciting information to build QnD scenarios, many different perspectives are expressed, each with its own assumptions about cause-effect relationships and beliefs about what potential interventions would constitute ecosystem improvement. The development process which involves working with stakeholders to build the model, play the game, and revise the model is undertaken within a soft systems approach. The soft systems approach distinguishes the QnD gaming and scenario-building process from the more traditional use of models as system predictors. The QnD development process can accommodate both hard data, such as field-measured experiments, and soft data, such as experiential learning, impressions or general "rules of thumb". The model is used to facilitate dialogue and learning about the factors that influence the environmental system under consideration, and to explore potential management actions.

While QnD has been used in a traditional simulation modeling context of simulating processes with the aim of reproducing measured field conditions and prediction of future conditions (Best *et al.*, 2004; Kiker and Linkov, 2005), the KNP and FooRiver case studies are provided in this chapter to show how QnD is configured to the wishes of different player and developer groups. The primary goal of these two versions is not necessarily to predict future ecosystem events with high precision, but to show the complexity of ecosystem management choices within a scenario context. Even under simplified object systems and spatial scales, adaptive management is a complex problem. The temptation to go against self-proclaimed policies at localized levels for short-term gains is constantly tempting especially when some level of political pressure is placed on management choices.

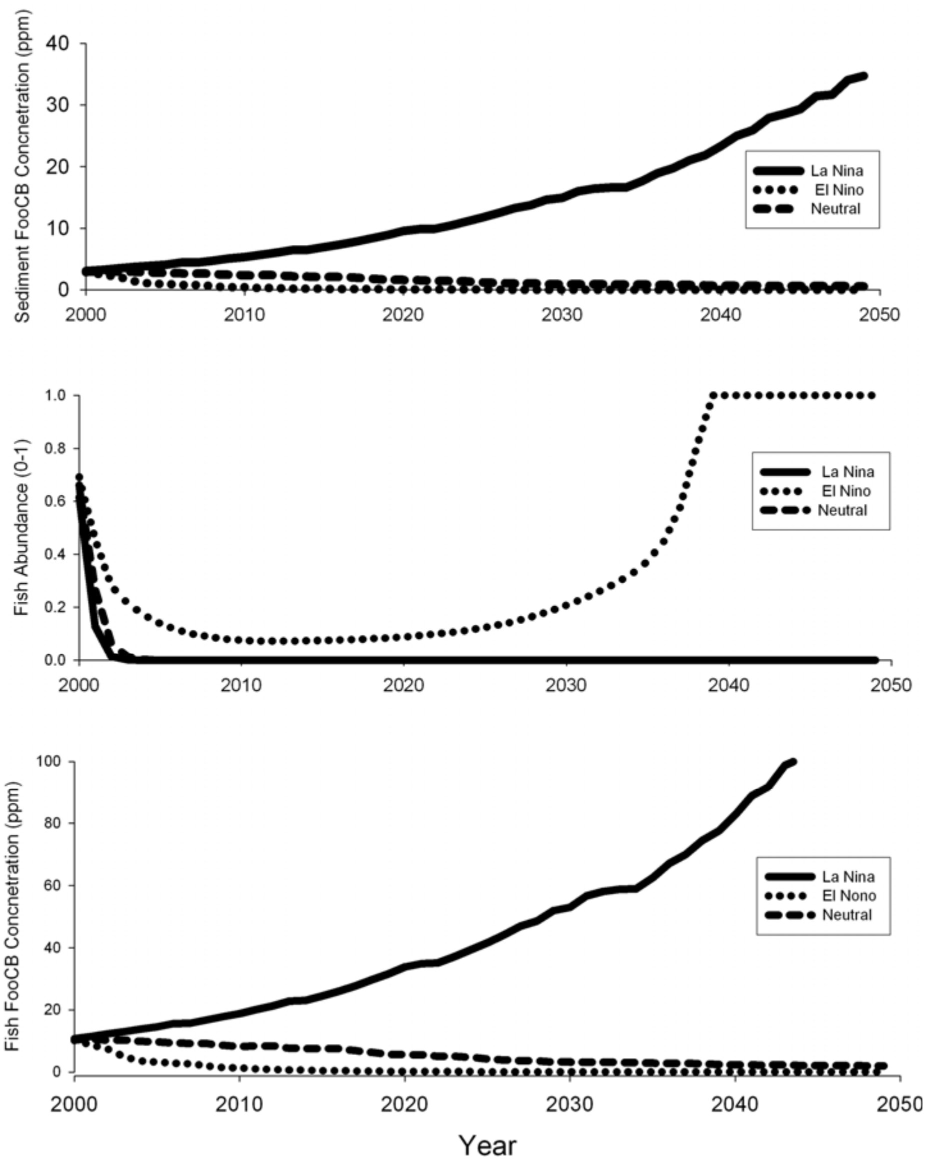

Figure 18. Example results from the QnD:FooRiver model (Shaka's Reach, three climate scenarios).

The role of external agents on management (*i.e.* "back-seat management") can influence and limit options quite directly. It may be beneficial to include these influences in QnD model design with similar attention that we might give to ecosystem dynamics and detail.

As mirrored within the QnD development methodology explored in this chapter, further development of the model system is ongoing. A more direct linkage with multi-criteria decision analysis is being developed to allow scenario-based exploration of various policies (collections of management actions that function under user set rules). One primary advantage of the player/developer/coder roles is that each group is able to innovate according to their function with the model development and game playing arenas. Players can expect a model that conforms more to their understanding of their world and future worlds with scenario development. Developers can design and implement objects to create a modular system that allows for testing and for changes to be quickly undertaken. Coders can work toward implementing technical advances that further the ease and power of model deployment within the internet-connected world.

An essential objective of QnD has been to actively involve many types of interested people in both model development and its subsequent execution to explore management scenarios. The model system strives to use different experiences and skill sets to an overall advantage in the decision-making process instead of limiting some stakeholders to outside roles of reviewers and/or critics. QnD is an evolving system that continues to develop as new groups of people interact with it to attempt to effectively manage and adaptively address wicked environmental challenges.

7. Acknowledgements

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