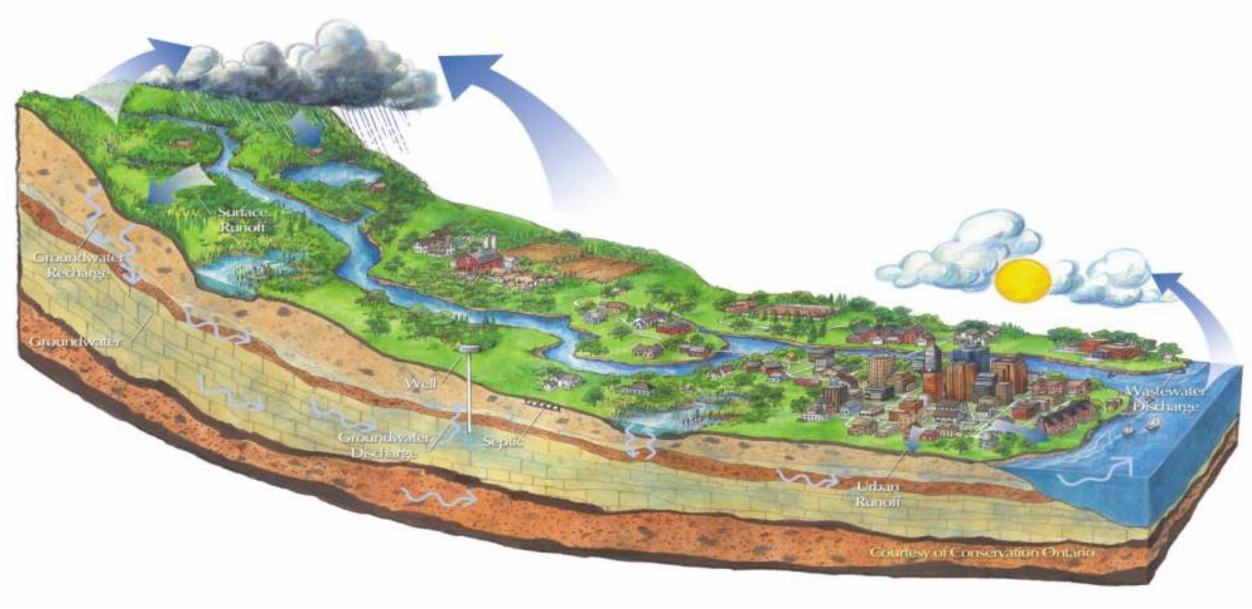
Sulis: A Framework for Healthy Watersheds Healthy Oceans Healthy Ecosystems

By the Northern Gulf Institute H^3O Team



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PREFACE

This report was prepared under award NA06OASR4320264 06111039 to the Northern Gulf Institute by NOAA's Office of Ocean and Atmospheric Research, U. S. Department of Commerce.

This work was performed with funding from the Northern Gulf Institute (NGI) project NGI06-MSU-03, Watershed Modeling Improvements to Enhance Coastal Ecosystems, and NGI06-MSU-04, Spatial Technology and High Performance Computing for Improving Prediction of Surface Water Quality, under the guidance of Principal Investigators Jairo N. Diaz-Ramirez, John Cartwright, Vladimir Alarcon, and William H. McAnally.

This document was prepared and reviewed by an interdisciplinary team consisting of William McAnally, James Martin, and Jairo-Diaz-Ramirez, Civil and Environmental Engineering Department; Albert J. Allen and Albert E. Myles, Department of Agricultural Economics; G. Wayne Wilkerson, Department of Landscape Architecture; John Cartwright, Rita Jackson, Vladimir Alarcon, and Philip Amburn, Geosystems Research Institute; Mary Love Tagert, Agricultural and Biological Engineering Department; John Harding, Northern Gulf Institute, and Arthur Cosby, Social Sciences Research Center; all at Mississippi State University; Julie Baca and Bernard Hsieh, U.S. Army Corps of Engineers; Stephen C. Sanborn and Christopher M. Wallen, Dynamic Solutions, LLC; and Jeff A. Ballweber, Pickering Engineering.

The cover graphic, used with permission courtesy of Conservation Ontario, depicts a watershed and adjoining ocean with the hydrologic cycle connecting the landscape with the aquascape and human activties.

During preparation of this report Dr. David Shaw was Director of the NGI and Dr. Michael Carron was Co-Director. Dr. John Harding is Chief Scientific Officer. The NGI web site is at http://www.northerngulfinstitute.org/home/ngi.php

EXECUTIVE SUMMARY

This document provides the framework and an action plan for Sulis, a computer-based water resources decision support system.

Sulis will provide users ready access to environmental and natural resources information in a useful form to better understand aquascapes and their processes, to evaluate the probable consequences of management decisions and natural change, and to make informed decisions with a holistic perspective. Healthy Watersheds – Healthy Oceans – Healthy Ecosystems is the underlying goal of Sulis.

The term “aquascape” is defined to be a complete hydrologic footprint, including a watershed – an area of the earth’s surface from which water flows downhill to a single outflow point – plus the water-spread – the coastal and ocean area over which the watershed’s flow spreads and ocean forcings affect coastal and upstream waters.

Expansion of the usual zones of concern from watershed-only and coastal/marine zone-only is necessary because of the holistic nature of water resources and the systems which depend on water -- ecosystems, economic communities, infrastructure, and social systems.

Water Resources is the total supply of surface and ground water suitable for use, and Water Resources Management as the process of ensuring that water of sufficient quantity and quality is available for beneficial uses. Management includes regulatory actions to conserve and protect water resources, planning to provide future resources, and actions and structures to store, divert, purify, and use water. We use the phrase “Holistic Aquascape Management” to denote the practice and process of achieving sustainable water resources use for the benefit of humans and the natural environment throughout the hydrologic footprint.

Water and land resources managers make decisions with far-reaching consequences. Too often they must make those decisions on the basis of information that is of poor quality, inaccessible, and/or incomprehensibly displayed. Sulis is a toolkit and systematic approach to holistic aquascape management, including tools for data assimilation and manipulation, modeling, visualization, and decision support.

As one example of typical water management decisions, state and federal agencies must permit or review projects that divert river flows to other purposes, such as irrigation or municipal water supply. Disapproval may limit economic development and produce adverse social impacts; however, approval may mean that minimum water flows for downstream water quality and quantity needs are not met, which can steepen river slopes, causing erosion and

land loss upstream, and impair water quality downstream, all with ecosystem, economic, and social impacts. Effects can extend upstream into the headwaters and downstream to lakes, estuaries and seas. For example, water use in the Apalachicola-Chattahoochee-Flint River Basin is the subject of a decades-long, well-publicized dispute among Florida, Alabama, Georgia, and the Federal government over conflicting priorities for water supply, hydropower, navigation, and habitat preservation all the way from Lake Lanier in Georgia to the Gulf of Mexico. Another example is the infamous hypoxic dead zone in the Gulf of Mexico, affecting fisheries throughout the Gulf, but caused by nutrients draining from dozens of states.

Sulis consists of five major components:

- User interface – a set of graphical screen displays to enable user input and to display results.
- Observed data – field observations from institutional databases such as USGS real-time and historical gauge data, EPA's BASINS, NOAA's NESDIS, and locally compiled and quality assured data.
- Models – Tools for predicting physical, biologic, economic, and social impacts of decisions and projects .
- Model Results Database – a local repository of specific model predictions which can be extracted and displayed and/or analyzed by the Inference Engine.
- Inference Engine – a program that evaluates user requests, fetches data, performs analyses, and generates new results for the user.

A user advisory group was formed to participate in all phases of system development from requirements through testing. Formation and use of such groups is a common usability practice that involves representative users directly in requirements, and also in design through testing. The key to the value of such groups lies in their careful composition to include the appropriate users, in this case, decision makers and managers.

Contents

1. INTRODUCTION

1.1. Objective

This document provides the framework and an action plan for Sulis[1], a computer-based water resources decision support system.

Sulis will provide users ready access to environmental and natural resources information in a useful form to better understand aquascapes and their processes, to evaluate the probable consequences of management decisions and natural change, and to make informed decisions with a holistic perspective. Healthy Watersheds – Healthy Oceans – Healthy Ecosystems is the underlying goal of Sulis.

Some key words in this objective include:

- “users” are those who manage water resources at the Federal, state, and local level; stakeholders who want to understand the effects of natural and anthropogenic changes and be able to influence policy and implementation; and those who advise both groups.[2]
- “ready access” which implies that a variety of users from technophiles to the technologically limited can operate the system at a simple level, at least, without having a computer specialist at their side.
- “natural resources information” which indicates a variety of information types (e.g., water quantity and quality, land use, biotic health) and formats (spreadsheets, GIS shape files, etc.)
- “useful form” which indicates that displays are informative and understandable, implying graphics.
- “aquascape” is used to indicate that the perspective is that of the complete hydrologic footprint, including that of a watershed – an area of the earth’s surface from which

[1] Sulis is the Celtic mythological goddess of wisdom, usually associated with the hot springs at Bath, England.

[2] Federal agencies include, but are not limited to, Environmental Protection Agency, Corps of Engineers, and Bureau of Reclamation National Oceanographic and Atmospheric Administration and its agencies, including the national Weather Service, Natural Resources Conservation Service, Forest Service, Fish and Wildlife Service, Minerals Management Service, and Park Service. State agencies include those responsible for water and environmental quality such as Mississippi Department of Environmental Quality and Alabama Department of Environmental Management. Local agencies include regional water districts, city and county/parish planning and environmental quality offices.

water flows downhill to a single outflow point – plus the water-spread – the coastal and ocean area over which the watershed's flow spreads and ocean forcings affect coastal and upstream waters.

- "holistic" is used to denote the fundamental interconnectedness of the water cycle, the physical environment, ecosystems, and human systems.

Sulis provides a systematic approach to holistic water resources management, including tools for data assimilation and manipulation, modeling, visualization, and decision support.

1.2. Background

Water and land resources managers make decisions with far-reaching consequences. Too often they must make those decisions on the basis of information that is of poor quality, inaccessible, and/or incomprehensibly displayed.

Though many tools exist for watershed management decision support, they each present certain limitations, discussed in more detail below. The most widely used of these tools include the Environmental Protection Agency's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (EPA 2009), a powerful tool for modelers, and the Corps of Engineers eCoastal (USACE 2009a), a Geographic Information System (GIS) repository of Corps data relevant to flood damage reduction, navigation and other Corps missions. Each offers unique capabilities, but each requires specialized skills and expertise to use, which reduces their utility for the typical decision-maker among the users identified in the Objective above.

Many simple tools exist for specific tasks, such as NOAA's N-SPECT, for nonpoint source pollution evaluation (NOAA 2009), The Corps of Engineers ACES (USACE 2009b), and MSU's Latis-Lidia (Wilkerson et al. 2009), for designing site management practices. Such tools can be enormously useful to those who know they are available and how to obtain them, but as standalone tools they seldom serve as a lingua franca for multiple stakeholders to communicate status, needs, and outcomes for complete systems.

Management and planning methods for coastal zones and oceans include Marine Spatial Planning (NOAA 2009) and Ecosystem Approach to Management (Levin et al. 2008), which bring a proven method to establishing and meeting resource management goals. Extension to upland areas, which strongly influence oceans, is a natural next step, but requires recognition of the fundamental interconnectedness of all aspects of the aquascape.

1.3. Scope

The justification, framework, component descriptions, initial user interface steps, and an action plan for Sulis are presented in six major Parts of this report.

Part 2 describes a few of the many efforts underway to manage water resources with a more holistic approach. It shows the compelling reasons to support these efforts with a tool set that enables resource managers, the users described above, to make better informed decisions and demonstrates why the Sulis architecture was adopted. It is based on work that the team has been doing for the past 10 to 40 years.

Part 3 examines water resources management, presenting typical issues, typical management decisions, and what kinds of support those decisions require. It is based on extensive stakeholder contributions to three Northern Gulf Institute (NGI) projects and a NOAA Coastal Services Center-funded project at Mississippi State University over the past 5 years.

Part 4 presents the internal architecture of Sulis, which has been generated by deliberations of the team under the present NGI project and is based in large part upon experiences of some of the team designing similar components and systems for the Corps of Engineers and Environmental Protection Agency. It includes a relatively new concept – an inference engine – which promises to revolutionize water resources decision support.

Part 5 presents initial work in designing a user interface in consultation with users, employing modern iterative prototyping.

Part 6 gives our conclusions and presents an action plan for completing construction of Sulis.

2. WATERSHEDS, OCEANS, AND HOLISM

Watershed management, coastal zone management, and marine management are often conducted in isolation, since their processes require different professional specialties and because they are subject to differing jurisdictions. Here we examine them separately first, and then discuss how good management requires that they be managed jointly.

2.1. Watershed Management

The term “watershed” is commonly used to describe an area of the earth’s surface from which water flows downhill to a single outflow point. The area encompassed may either be small, such as that which an ephemeral stream drains only during precipitation events, or be large, such the Mississippi River Valley, which drains nearly half the United States through the Mississippi River and its thousands of tributary rivers and streams. Although some attempts have been made to create a hierarchical system of terms based on size, such as catchment, watershed, sub-basin and basin, a systematic nomenclature has not gained widespread acceptance, except for the numerical Hydrologic Unit Code (HUC) employed by the U.S. Geological Survey (USGS 2009). Figure 2-1 shows the southeastern U.S. with its myriad streams and Mobile Basin watershed’s sub-watershed 8-digit HUCs identified. Although the Tennessee River is part of the Mississippi River watershed, in this figure it is shown as connected to the Mobile Basin because of the release of navigation lockage water from the Tennessee into the Tombigbee River, a tributary to Mobile Bay.

As used here, the term Water Resources is defined as the total supply of surface and ground water suitable for use, and Water Resources Management as the process of ensuring that water of sufficient quantity and quality is available for beneficial uses. Management includes regulatory actions to conserve and protect water resources, planning to provide future resources, and actions and structures to store, divert, purify, and use water. Beneficial uses subject to management include the traditional classifications of agricultural, industrial, municipal, hydropower, navigation, and recreation plus environmental quality and habitat. Storm and flood damage reduction, representing the inverse problem of too much water or water in the wrong place, is also included in the water resources management definition. Figure 2-2 illustrates a schematic watershed and associated coastal zone with important elements of the hydrologic cycle and human modifications.

Other resources, ranging from minerals to trees to fish, either affect water resources (e.g., mine leachate entering streams) or are affected by them (e.g., coastal and shelf fish habitat), so activities that might be called natural resources management are closely related to water resources management. Similarly, since economic development hinges upon adequate water supplies among other resources (such as labor and transportation) and affects water resources through water usage and changes in land use, economic development is inextricably linked with water resources and water resources management.

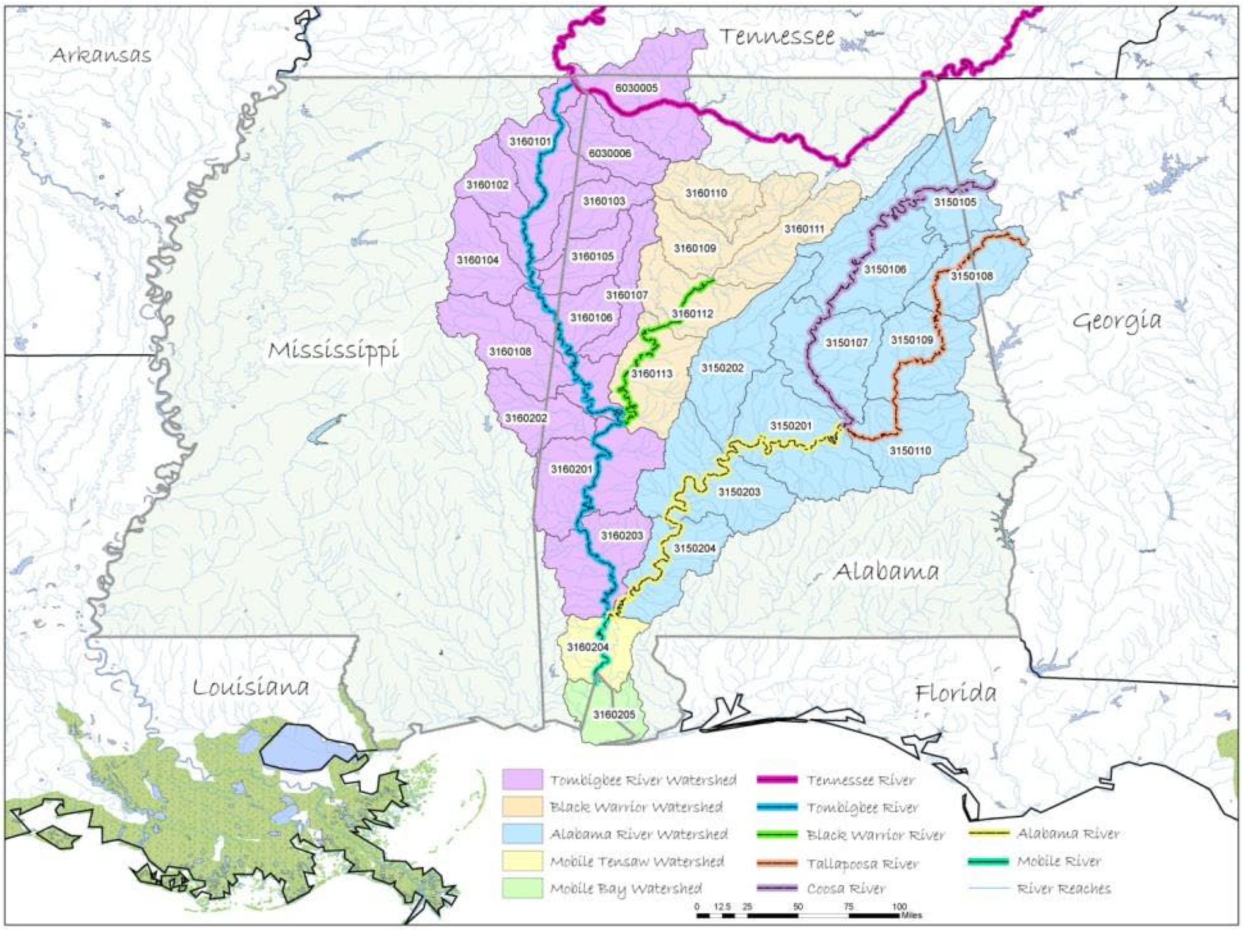

Figure 2-1. Mobile Basin watershed with 8-digit Hydrologic Unit Codes (HUCs) identified

With the water system, ecosystem, and human systems so interconnected, and with actions at one location affecting those systems even at substantial distances, managing water resources from a watershed perspective is essential, as has been widely recognized.

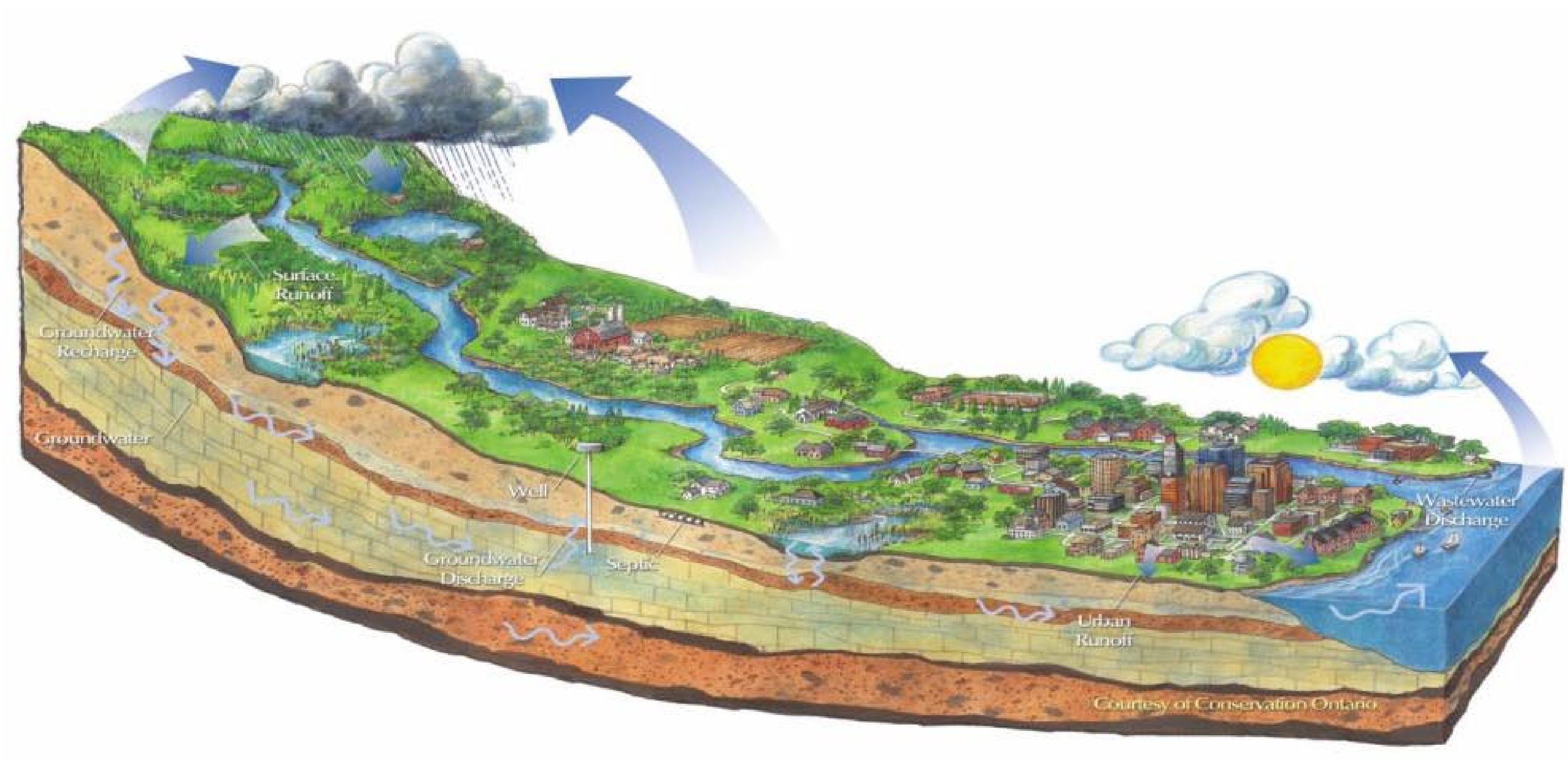

Figure 2-2. Watershed schematic with hydrologic cycle and human alterations. (Courtesy of Conservation Ontario, by permission)

Management of water resources from a watershed perspective is related to concepts and terms such as “integrated water resources management,” “total water management,” “watershed management,” and “regional management.” Total Water Management is defined by the American Water Works Association Research Foundation (AWRA 1996) as

> *…the exercise of stewardship of water resources for the greatest good of society and the environment. A basic principle of Total Water Management is that the supply is renewable, but limited, and should be managed on a sustainable-use basis.*

The AWRA definition includes the concept of sustainability, which the American Society of Civil Engineers defines for water resources as:

> *Sustainable water resource systems are those designed and managed to meet the needs of people living in the future as well as those of us living today.*

A frequent criticism of the sustainability concept is that it’s idealistic and impossible — any use of resources is bound to decrease the amount available to future generations. However, that criticism is no more valid than saying that we need not strive for safety, since perfect safety is never achieved. Absolute environmental sustainability can be an ideal goal that is balanced with economic development and the cultural fabric of a region, which are implicitly included in the above sustainability definition.

The Corps of Engineers (USACE 2000) defines watershed perspective planning as:

> *… accomplished within the context of an understanding and appreciation of the impacts of considered actions on other natural and human resources in the watershed. In carrying out planning activities, we should encourage the active participation of all interested groups and use of the full spectrum of technical disciplines in activities and decision-making. We also should take into account: the interconnectedness of water and land resources (a systems approach); the dynamic nature of the economy and the environment; and the variability of social interests over time. Specifically, civil works planning should consider the sustainability of future watershed resources, specifically taking into account environmental quality, economic development and social well-being.*

Another term that leads to many of the same conclusions as the watershed perspective is “systems,” sometimes expressed as systems thinking, systems engineering, etc. and appears in the Corps of Engineers’ definition above.

The Tennessee Valley Authority is often cited as the model for managing a watershed for multiple purposes. Chartered by the Federal government in 1933, its intended purpose was "… in the interest of the National defense and for agricultural and industrial development, and to improve navigation in the Tennessee River and to control the destructive flood waters in the Tennessee River and Mississippi River Basins, …" (U.S. 1933). President Franklin Roosevelt, in his request to Congress for the authorizing legislation, said, "It should be charged with the broadest duty of planning for the proper use, conservation, and development of the natural resources of the Tennessee River drainage basin …" (Roosevelt 1933). True to his vision, TVA became an engine for not just economic growth, but also education, cultural preservation, and environmental stewardship, all centered around water management.[3]

2.2. Coastal and Marine Resources Management

Management of coastal and marine resources, like that of watersheds, encompasses a variety of biotic and abiotic resources ranging from marine benthic organisms to fisheries to recreational beaches to ports. NOAA's Office of Coastal and Ocean Resource Management expresses the scope of needs as:

> *Our coasts are facing increasing pressures from pollution, habitat degradation, over-fishing, invasive species, and coastal hazards, including hurricanes and sea-level rise. The increasing coastal population can also create conflicts between often competing coastal uses: beach goers, commercial and recreational boaters, residential, commercial, industrial and port development. The challenges ocean and coastal managers face of balancing coastal uses while protecting valuable coastal resources are mounting.* (NOAA OCRM 2009)

These challenges need integrated solutions no less than those of the watersheds described in the preceding section, and several excellent conceptual approaches have arisen to meet those needs, including two related approaches supported by NOAA – Ecosystem Approach to Management and Coastal and Marine Spatial Planning.

Ecosystem Approach to Management (EAM) begins with a process called Integrated Ecosystem Assessment (IEA) described by Levin et al. (2009) as:

[3] Recently TVA has been criticized for becoming just another power company willing to sacrifice the common good for revenues, but its accomplishments are widely recognized. (e.g., Hargrove 2001; Miller and Reidinger 1998)

… a critical science-support element enabling an EAM strategy. An IEA is a formal synthesis and quantitative analysis of information on relevant natural and socio-economic factors in relation to specified ecosystem management goals. It involves and informs citizens, industry representatives, scientists, resource managers, and policy makers through formal processes to contribute to attaining the goals of EAM.

IEA follows a five-step process, grounded in stakeholder involvement, which identifies a circularly dependent sequence of Drivers, Pressures, States, Impacts, and Responses of ecosystems as shown in Figure 2-3. IEA have been applied to systems as diverse as the coastal waters of New Jersey and California, the inland Columbia River Basin, and Lake Ontario in North America and to ecosystems in Africa.

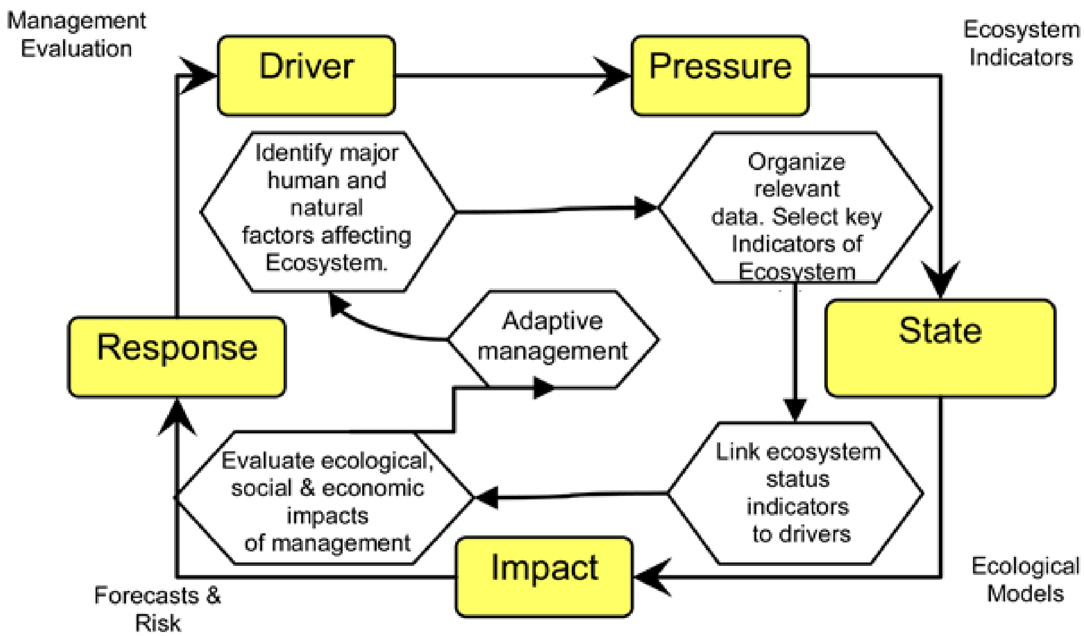

Figure 2-3. Framework for IEA (Source: NOAA 2009a)

Marine Spatial Planning is defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as:

… a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological,

> *economic and social objectives that have been specified through a political process.* (UNESCO 2009)

The President's Council of Environmental Quality (CEQ 2009) describes Coastal and Marine Spatial Planning (CMSP) as:

> *CMSP is a comprehensive, adaptive, integrated, ecosystem-based, and transparent spatial planning process, based on sound science, for analyzing current and anticipated uses of ocean, coastal, and Great Lakes areas. CMSP identifies areas most suitable for various types or classes of activities in order to reduce conflicts among uses, reduce environmental impacts, facilitate compatible uses, and preserve critical ecosystem services to meet economic, environmental, security, and social objectives. In practical terms, CMSP provides a public policy process for society to better determine how the ocean, coasts, and Great Lakes are sustainably used and protected now and for future generations.*

NOAA has identified three essential attributes for effective CMSP:

- *Multi-objective. Marine spatial planning balances ecological, social, economic, and governance objectives.*
- *Spatially focused. The ocean area to be managed must be clearly defined and large enough to incorporate relevant ecosystem processes.*
- *Integrated. The planning process should address the interrelationships and interdependence of each component within the defined management area, including natural processes, activities, and authorities.* (NOAA 2009b)

Four U.S. states – Oregon, California, Florida, and Rhode Island – have begun work on constructing CMSP plans in partnership with NOAA. Oregon's initial focus has been on wave energy efforts, California's is marine life protection, with a special pilot project in San Pablo Bay (part of the San Francisco Bay system), and Rhode Island's is on ocean resources, primarily fisheries. Florida has focused on the Florida Keys, protecting natural resources, including the coral reef, from pollution and damage from fishing, tourism, and petroleum exploration. The planning process has much in common with the Ecosystem Approach to Management and its Integrated Ecosystem Assessment – data gathering, extensive stakeholder involvement, and collaborative decision making. The "spatial" distinction is significant in these efforts, with Geographic Information System (GIS) display and analyses, including the interagency Multi-purpose Marine Cadastre (NOAA 2010), playing a key role.

It is widely accepted that healthy watersheds are necessary (but not sufficient) for healthy oceans. The infamous Dead Zone in the Gulf of Mexico is usually ascribed to the flow of nutrients from the Mississippi River watershed, the largest in North America. If that is the cause, then we must improve the health of the watershed in order to improve the Gulf's health.

2.3. Healthy Watersheds, Healthy Oceans, Healthy Ecosystems

The preceding two sections addressed essentially the same topic – attempts to gain a more integrative perspective on managing our natural and built environments for maximum mutual benefit – but used terms specific to the geographies of watersheds and oceans. In fact, the two geographies are difficult to separate, since they are hydrologically coupled, as illustrated in Figure 2-2. They are simply two geographies of the hydrologic cycle – a watershed and a water-spread – connected not only by the atmospheric components of evaporation, condensation, and precipitation, but by the physical processes, economic systems, and ecosystems that overlay them.

Efforts at managing from a watershed or larger coastal/ocean zone perspective as described above are encouraging. Multiple organizations are trying to move beyond the single project, single sector perspectives that have too long dominated water resources discussions. Projects have consequences at great distances, as demonstrated by disputes over Lake Lanier water among the states of Georgia, Alabama, and Florida and Federal agencies ranging from the Corps of Engineers to Fish and Wildlife Service. Disputes between advocates for economic development and the endangered pallid sturgeon of the southeast provide grist for multiple court disputes and internet debates as advocates for single sectors make their respective cases.

As essential as they are, efforts to use a broader, more inclusive perspective also raise the question of where to draw the boundaries of a broader examination. Aside from questions of scalability (see discussion later in this document), we must balance our need to see the bigger picture with our ability to properly grasp what we are seeing. If we begin by paraphrasing Jacob Marley's cry[4] to say that the "whole earth is our business," we have properly recognized that the earth is an interconnected ecosystem, but have also overstepped our abilities to manage or even understand how it works. Key to successful water resources management is setting the boundaries of concern large enough, but no larger.

We believe that the proper perspective for water-related management is the hydrologic footprint, or aquascape: the landscape over which water flows to the ocean, the coastal and

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[4] "Mankind was my business!" (Dickens 1843)

ocean zone over which that water spreads and carries the material acquired during its journey from upland to the sea, and effects of the seas upon the coast. The aquascape perspective supports and reinforces integrated watershed management in its many forms, from Total Water Management to Marine Spatial Planning and Ecosystem Approach to Management.

Within the boundaries of an aquascape, water resources management must consider at least safety, economics, culture, and ecosystems, as decided by our society, mostly expressed through laws (see Section 4.3) . How we consider these systems and their interactions is a key challenge. Eugene Odum, one of the great pioneers of modern ecology and author of *Fundamentals of Ecology* (Odum 1953) employed the concept of interdependence of all the actors on the stage, biotic and abiotic, a concept also known as holism.

The word holistic has often been misused, but is so uniquely descriptive of what this work strives for that we are compelled to use it. Derived from the Greek *holos*, meaning “altogether” or “entire,” which was defined by Aristotle (350 BCE) as, “the whole is greater than the sum of the parts.” Jan Smuts[5] (1926) is credited with coining the English term holism, which he described as "the tendency in nature to form wholes that are greater than the sum of the parts through creative evolution.” The definition has been refined and applied in diverse fields, most vividly by Douglas Adams (1987) as the "fundamental interconnectedness of all things.” Adams’ definition helps to remind us first, that economies and ecosystems are fundamentally connected as interacting contributions to the quality of life, and second, that what happens in one part of an aquascape affects other, often unseen aspects and areas of the aquascape.

Smuts’ concept of holism was much more than interconnectedness. He described it as the “… ultimate synthesizing, ordering, organizing, regulating activity in the universe …” seeing it as an active force, responsible for organizing “wholes.” He defined wholes as “… composites which have an internal structure, function, or character which clearly differentiates them from mere mechanical additions or constructions ….” Wholes include a water molecule (more than a simple mixture of hydrogen and oxygen atoms), cells (more than a collection of water, minerals, and organic molecules), an organism (more than a collection of cells), and so on until the summation of wholes becomes the universe. We add ecosystems, societies, and aquascapes to the list. Figure 2-4 illustrates a few graphics which attempt to capture aspects of the holistic view.

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[5] Smuts was a military leader, statesman (the only person to sign the charters of both the League of Nations and United Nations), and scholar (Albert Einstein said that Smuts was one of only 11 people in the world who understood the Theory of Relativity).

Examples of the interconnectedness of Smuts' "wholes" abound.

- Paine (1966) reported on a set of coastal ecosystems in which 15 large species existed in relative equilibrium. Removing the starfish from some of the systems resulted in a crash so severe that one year later only 8 species dominated, while the control systems remained in balance.
- Savory (1999) describes a lush, wildlife-rich Luangwa Valley in Zambia that was converted to a national park and game preserve by relocating local hunting and farming villages. Within a few decades the landscape became denuded of vegetation, serious riverbank erosion occurred, and game species all but disappeared, after villagers were replaced by park employees and tourists.
- Weins and Roberts (2003) attribute the decline of bottomland hardwood wetlands along the Wolf River in Tennessee to headcutting, a stream erosion process that moves from a downstream disturbance (such as channelization) to upstream areas far from the original disturbance.

We use the phrase "Holistic Aquascape Management" to denote the practice and process of achieving sustainable water resources use for the benefit of humans and the natural environment throughout the hydrologic footprint, or aquascape.

2.4. Why Healthy Watersheds – Healthy Oceans – Healthy Ecosystems?

The above sections marshal evidence to show that an aquascape perspective is the appropriate view for managing water resources and those systems that depend on water. For example, since land use affects water quantity and quality, water resources management must necessarily consider aspects of land management issues, including zoning, building codes, highways, etc.

Since Sulis is intended for water resources management, organizing it with a aquascape perspective makes imminent sense – water should be managed as a Smuts-type whole. Management at the aquascape level is a sensible way to proceed, with a few caveats.

One caveat is that large aquifers often transcend aquascape boundaries, so management of ground water may, in some circumstances, require an even larger perspective. Another is that ecosystems do not have boundaries along aquascape lines, nor do human communities, so where the aquascape processes intersect ecosystems and human communities (including the economic and political systems) a perspective larger than aquascapes may be needed. For example, migrating waterfowl traverse many aquascapes each year.

Political boundaries, which often divide water management responsibilities across multiple jurisdictions,[6] almost guarantee conflict and mismanagement. While political boundary challenges can't be eliminated by a decision support tool, they can be ameliorated by tools that enable all interested parties to see the same data, so that negotiation can focus on balancing outcomes.

We use the phrase, "Healthy Watersheds – Healthy Oceans – Healthy Ecosystems" (abbreviated H^3O) as the underlying goal of Sulis and use the double water drop (to depict the watershed and water-spread aquascapes) in a circle (to depict the ecosystems and human systems which depend on them) for its symbol, as shown in Figure 2-5.

[6] New Zealand is a notable exception. Administrative units have been organized by watershed boundaries since 1868 (NAP 1999).

Figure 2-4. Holism envisioned in various ways. Top: Mosaic of Emperor Constantine (in Hagia Sophia, courtesy of About.com) with tile detail enlarged. Middle: a circular “Whole” consisting of many individual Wholes, the complementary Yin and Yang of the Tao, Bottom: a rhomboid depiction of issues that contribute to a aquascape’s wholeness.

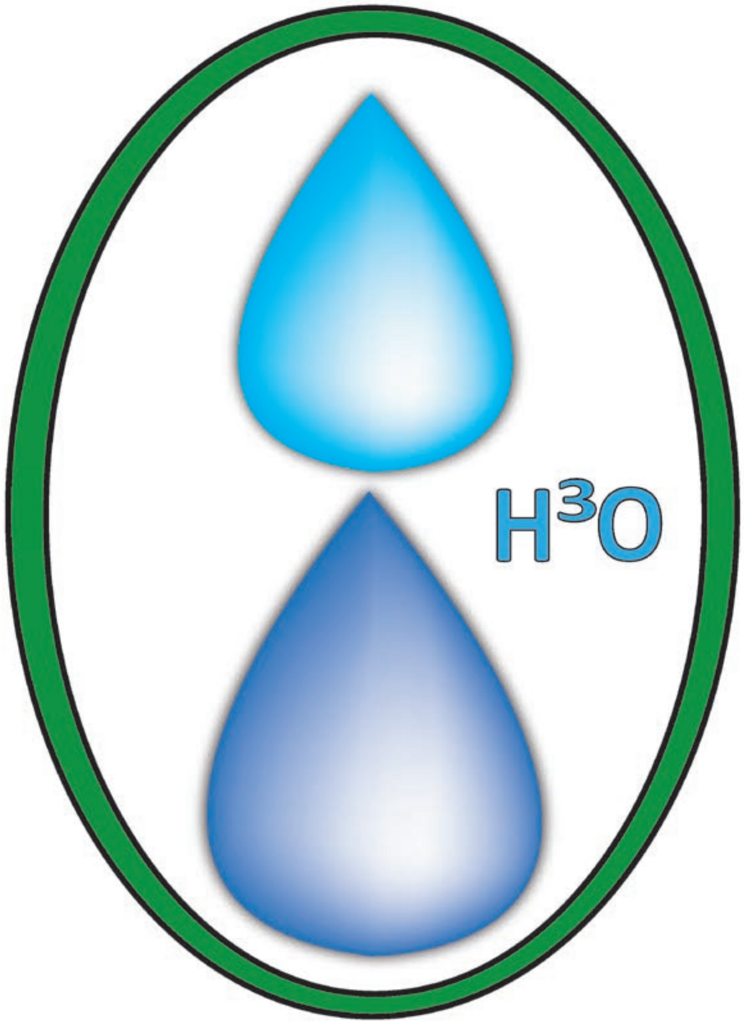

Figure 2-5. Sulis H^3O Logo with droplets depicting the aquascape of watersheds and water-spreads (coastal and ocean zones) enclosed in an ellipse depicting the systems that surround and interact with water – ecosystems, social systems, economic systems, and infrastructure.

3. WATER RESOURCES MANAGEMENT

3.1. Issues

Water resources managers make decisions with far-reaching consequences. To make those decisions well, they need complete, accurate information, readily accessible and understandably displayed. The issues driving this work are the gaps between these needs and available information and tools and the dichotomy between the holistic character of natural systems and the present piecemeal approach to management of all resources.

3.1.1. Typical Management Decisions

As one example of typical water management decisions, state and federal agencies must permit or review projects that divert river flows to other purposes, such as irrigation or municipal water supply. Disapproval may limit economic development and produce adverse social impacts; however, approval may mean that minimum water flows for downstream water quality and quantity needs are not met, which can steepen river slopes, causing erosion and land loss upstream, and impair water quality downstream, all with economic and social impacts. Effects can extend upstream into the headwaters and downstream to the lakes, estuaries and seas. For example, water use in the Apalachicola-Chattahoochee-Flint River Basin is the subject of a decades-long, well-publicized dispute among Florida, Alabama, Georgia, and the Federal government over conflicting priorities for water supply, hydropower, navigation, and habitat preservation all the way to the Gulf of Mexico.

Some other examples of water resources decisions are:

- Plans for reducing stream flooding
- Permit a wastewater discharge
- Permit an impounding dam
- Operating rules for reservoir releases
- Plans for channel deepening, straightening, or structural control
- Codes for gutters and storm drains in subdivision construction
- Permit to fill wetlands
- Permit for surface water intake
- Consolidation of small water systems
- Fishing Restrictions
- Tourism restrictions
- Permit for ocean placement of dredged material

Example management decisions not usually considered to be water resources matters, but which may affect water resources include:

- Codes for erosion control measures during site clearing and construction (affect runoff rate and sediment supply)
- Zoning restrictions on building type and size, parking facilities (affect runoff rate, groundwater recharge, and sediment supply)
- Tillage practices, crop selection, and operations in agriculture, home lawn care, and recreational turf (affect runoff rate and nutrient, pesticide, fertilizer, and sediment loads)
- Transportation improvements and associated suburban growth (affect stream crossings, nutrient and toxic pollutant loadings, and flooding)
- Port expansion (increases vessel traffic, may require channel enlargement)
- Wildlife management
- Aquaculture permitting (both on and offshore)
- Renewable energy permitting

3.1.2. Decision Support Needs

Despite far-reaching effects of decisions and practices like those above, water resources managers must often perform their jobs and make decisions without all the critical information and essential supporting tools. They often do not know how much water is available, and cannot accurately identify and quantify upstream and downstream effects of their decisions. To make informed decisions, they need more complete, accurate data, understandably displayed. Those data often come from sophisticated, time-consuming field and model studies, requiring outside experts. Even when the data and model results are available, they typically can be accessed only by computer experts.

Integrated ecosystem assessment method approaches need information on the following (Levin et al. 2009):

- States – indicators of existing conditions for a multitude of measures which may vary in time and space, such as water quantity, impaired waters (e.g., EPA 303d lists of impaired waters), waterbody characteristics, habitat type, and species abundance.
- Drivers – factors that cause system changes, such as climate change, channel improvements, impoundments, land use, and diversions.
- Pressures – factors such as pollution and fishing effort that result from Drivers and cause impacts.

- Impacts – changes in states, such as reduced recreation, decrease in biodiversity, loss of fishing communities, and economic dislocation.

Each of these categories includes information about the environment that is:

- Physical (e.g., amount and quality of water)
- Biotic (e.g. health of individual species and ecosystems)
- Economic (e.g., costs of projects and inaction, local, regional, and national economic benefits)
- Social (e.g., cultural preservation, health, economic justice, laws)

3.2. Available Decision Support Tools

The Environmental Protection Agency (EPA) provides a widely used decision support tool for water resource management, Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (EPA 2009). The BASINS user interface is illustrated in Figure 3-1. The tool is powerful, enabling the user to download information from EPA, USGS, and NOAA databases on watershed characteristics, prepare analyses, and display results. It is limited, however, by largely static databases and a learning curve that many occasional users, such as agency decision-makers, find cumbersome. It is most useful to modelers who use the tool frequently, and are thus adept with the many steps and nuances required to appropriately integrate data and model results.

Another resource available for decision support, the Corps of Engineers eCoastal GIS system, is an excellent repository of Corps data germane to storm damage reduction, navigation, and other Corps' missions. While simpler to use than BASINS, it requires a level of GIS experience and training that not all managers possess. An example for Mobile Harbor bathymetry is shown in Figure 3-2.

The Earth System Modeling Framework (ESMF) is a multi-organization collaboration for software infrastructure that enables earth sciences models and data to be coupled in a standard architecture. It is not a decision support too, but rather a collection of tools and methods for constructing a decision support tool like Sulis from multiple components. (ESMF 2009) Figure 3-3 shows the structure of the NASA GEOS-5 Atmospheric General Circulation Model, built using ESMF.

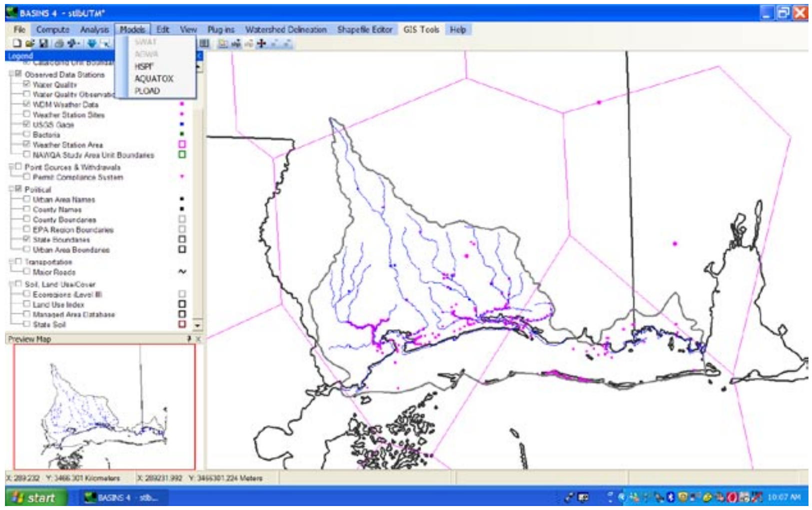

Figure 3-1. BASINS Interface Sample Screen

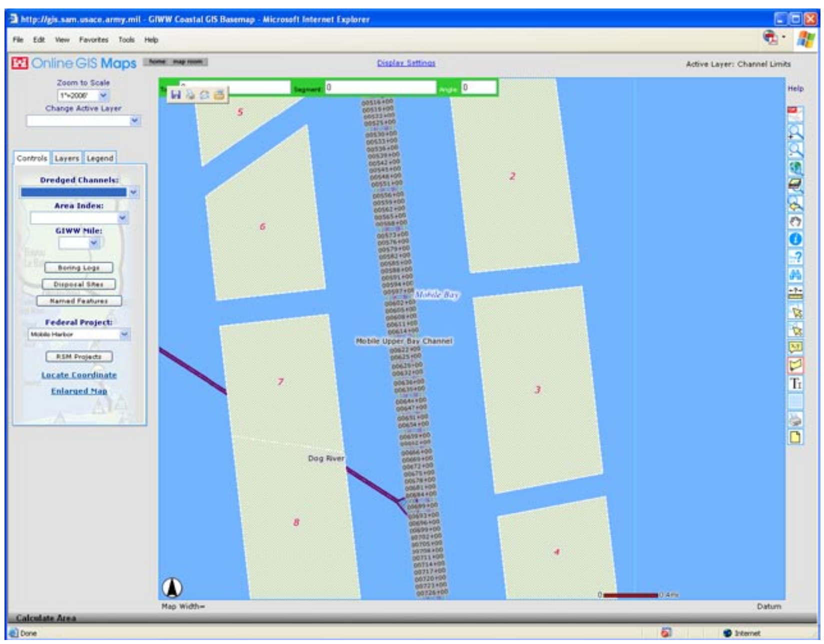

Figure 3-2. eCoastal GIS Example Screen (Source: U.S. Army Corps of Engineers)

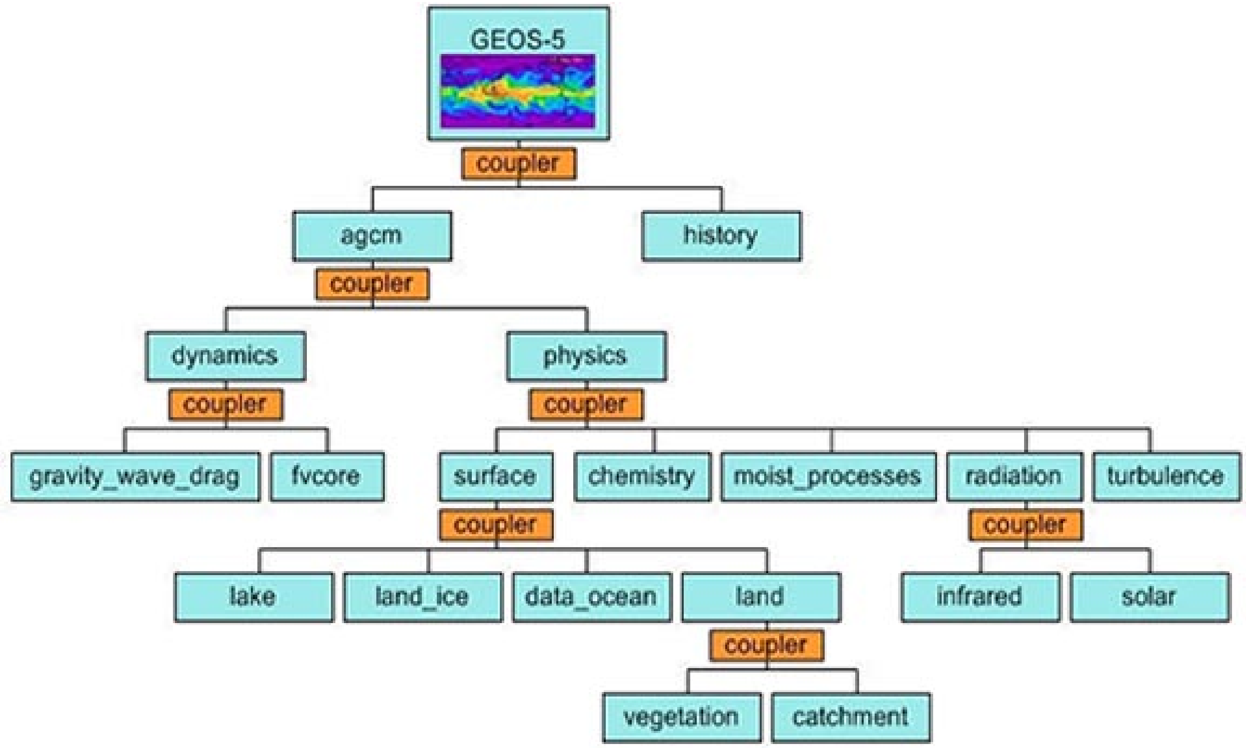

Figure 3-3. NASA GEOS-5 General Circulation Model, built using ESMF (ESMF 2009).

Many simple tools are also available that address a primary question. Of many examples, NOAA's Coastal Services Support Center offers N-SPECT, a tool for examining water quality impacts from development and climate change (NOAA CSC 2009), and the Corps of Engineers offers ACES, a collection of coastal engineering tools (USACE 2009b).

The Multipurpose Marine Cadastre (NOAA 2010) provides a viewer and database of submerged lands information, including legal boundaries, infrastructure, and biotic resources in a GIS format, as shown for the Mobile Bay – Mississippi Sound area in Figure 3-4.

In the aggregate, the variety of available tools and models can address part of the gap between needs and capabilities, but taking advantage of them requires both knowledge of what is available and training in a multitude of technologies. A single source with a single, simple interface is needed. Sulis will provide such an interface.

Several management approaches, including Integrated Watershed Management, Regional Sediment Management, Marine Spatial Planning and Ecosystem Approach to Management, follow well-proven standard procedures that provide structure for the process and produce results appropriate for the need. These procedures are structured consistent with the concepts and terminology of quality management summarized in the Shewhart Cycle, described by W. Edwards Deming (1986) as "Plan, Do, Study, Act," an iterative process displayed in Figure 3-5.

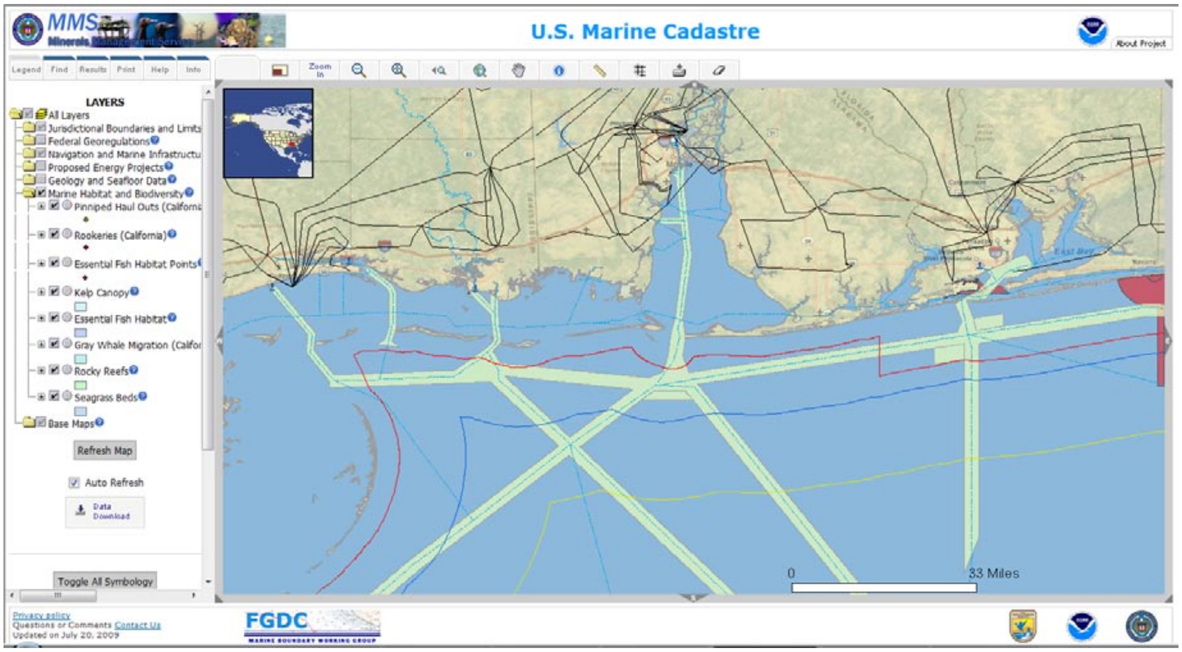

Figure 3-4. NOAA Multipurpose Marine Cadastre Example Display for Mobile Bay area.

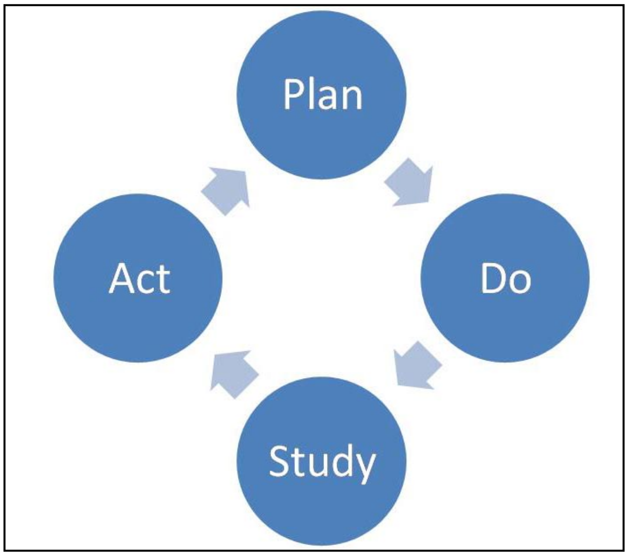

Figure 3-5 Illustration of the Deming-Shewhart Cycle.

The initial “Plan” step follows these steps, which are executed in collaboration with stakeholders:

1) Specify the area of interest
2) Define issues of concern
3) Establish objectives
4) Prescribe requirements to meet the objectives.

The Do step implements the Plan, the Study step measures progress according to defined metrics and identifies needed improvements, the Act step specifies modifications to the Plan, and the cycle continues indefinitely, reacting to changes from inside and outside the system.

These steps have become so ingrained in so many fields that they have become almost automatic components of any thoughtful process. Through the cycle, management decisions can proceed by comparing conditions with requirements appropriate to the area of interest, issues, and objectives with full stakeholder participation. Marine Spatial Planning, described earlier, employs these steps.

3.3. Scaling

Scaling of processes and management plans presents challenges in choosing a boundary for the area of interest, as discussed in Section 2.3, which was resolved with definition of aquascapes, and also with the spatial and temporal resolution of processes. Figure 3-6 illustrates a part of the challenge with a depiction of how various processes related to sediment transport correlate in space and time. With a few exceptions, large spatial scale processes are best understood at long time scales, and vice-versa. Further, knowledge at one scale often doesn’t provide insights at other scales. For example, detailed understanding of bed forms, important at local scales, does not significantly inform our understanding of delta formation processes. There are connections between the two, but our understanding of those connections is limited.

Scale also affects our understanding and modeling of many processes. For example, a single Apalachicola Bay oyster fisherman understands a great deal about the oysters and area he harvests from, but that knowledge is of limited use to the U.S. Fish and Wildlife manager responsible for overall Gulf of Mexico fisheries health.

Another example is offered by water databases. Because of budget reductions for data collection over the last four decades, numerous stations have been closed or operated intermittently. Finding data sets with equivalent periods of record, time intervals, and quality control has become a substantial problem for anyone seeking to understand the quality and quantity of water resources. A means of overcoming this difficulty is needed.

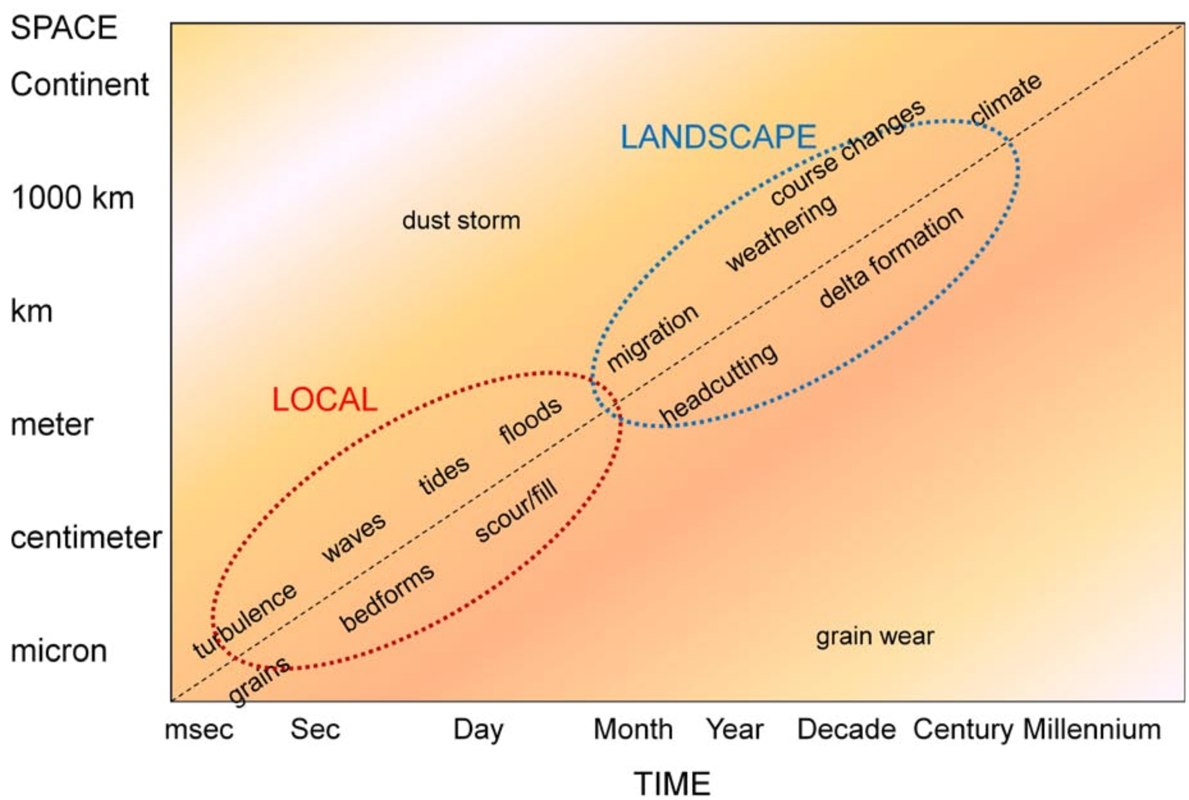

Figure 3-6. Comparable time and space scales for processes related to sediment transport.

4. SULIS ARCHITECTURE

Sulis is designed to satisfy the needs for holistic water resources management at the aquascape scale as described in Parts 2 and 3.

4.1. Introduction

An architectural diagram for Sulis is shown in Figure 4-1. It consists of five major components listed here and discussed further in the succeeding sections:

- User interface – a graphical, three-layer set of screen displays to enable user input and to display results.
- Observed data – field observations from institutional databases[7] such as USGS real-time and historical gauge data, EPA's BASINS and Storet, and NOAA's NESDIS or locally compiled and quality assured data.
- Models – Tools for predicting impacts of decisions and projects.
- Model Results Database – a local repository of specific model predictions which can be extracted and displayed and/or analyzed by the Inference Engine.
- Inference Engine – a program that evaluates user requests, fetches data, performs analyses, and generates results for the user.

Sulis consists of standard software components, used in every application, and custom components, specific to the aquascape of interest. The user interface and inference engine have a standard design. Models and data from models and observations are custom components for the aquascape. For example, Sulis for the Atchafalaya Basin and Sulis for the Mobile Basin would share the same basic toolset in the user interface and inference engine, but each would have its own models and databases unique to their location.

4.2. User Interface

The User Interface will be designed for simplicity and ease of use through user-centered requirements definition and prototyping as described in Section 4. It is envisioned to be based on public domain, light GIS software, such as ESRI ArcGIS Explorer, Google Earth, and others. A prototype screen for the Mobile River Basin is shown in Figure 4-2.

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[7] Institutional databases will be accessed through hyperlinks and downloads, not by recreating those databases.

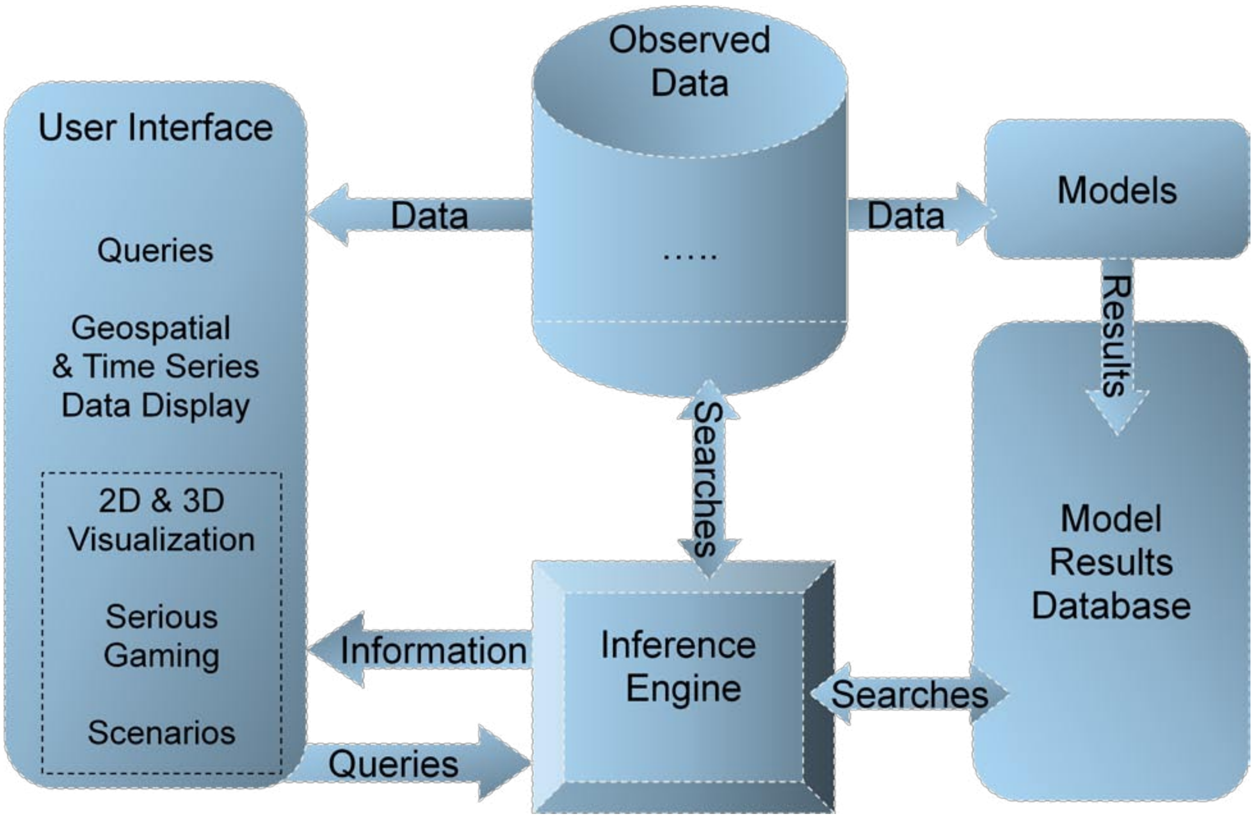

Figure 4-1. Sulis Architecture

As shown in Figure 4-2, user queried displays are a fundamental use of the interface, in which the user sees the aquascape of interest and employs light GIS technology to overlay items of interest, such as geographic information (streams, roads, etc.), water project features (dams, withdrawals, etc.), and impairments (e.g., EPA 303d-listed waters). Such static spatial data displays in GIS form are well-developed and widely used. For example, displays combining flood inundation maps with residential areas readily shows areas of interest for flood protection and insurance decisions.

Observed Data displays are another widely employed GIS layer, with USGS and others displaying gage locations on GIS-type display. Figure 4-3 shows the USGS-Google water data map for the Mississippi-Alabama-Georgia region in which the data station symbols display station statistics when the cursor passes over them. The “Data” menu in Sulis will provide hyperlink access to data from USGS, NOAA, NASA, EPA, Corps of Engineers, and other agencies with data storehouses.

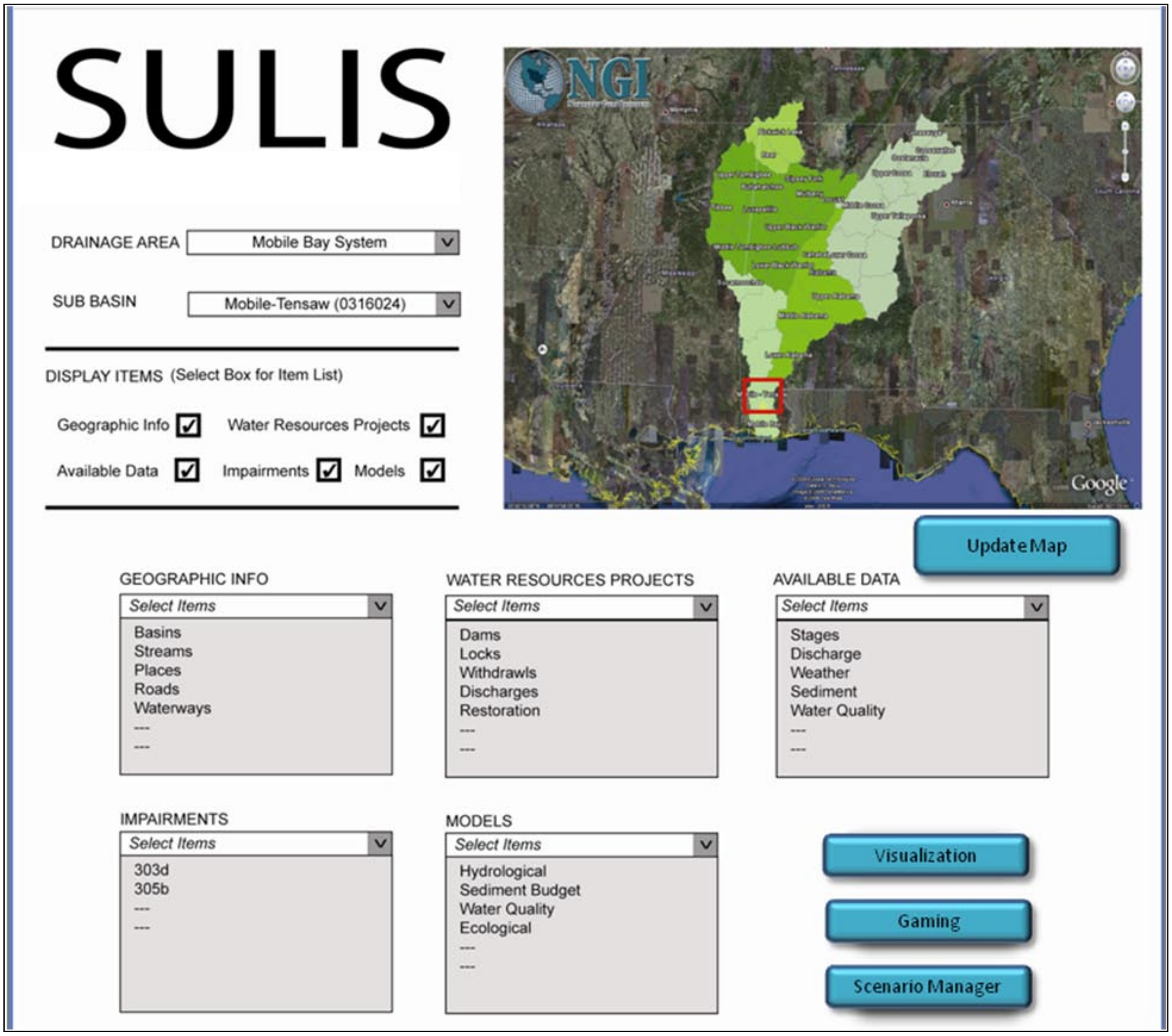

Figure 4-2. Prototype Sulis User Interface Screen for Mobile Bay

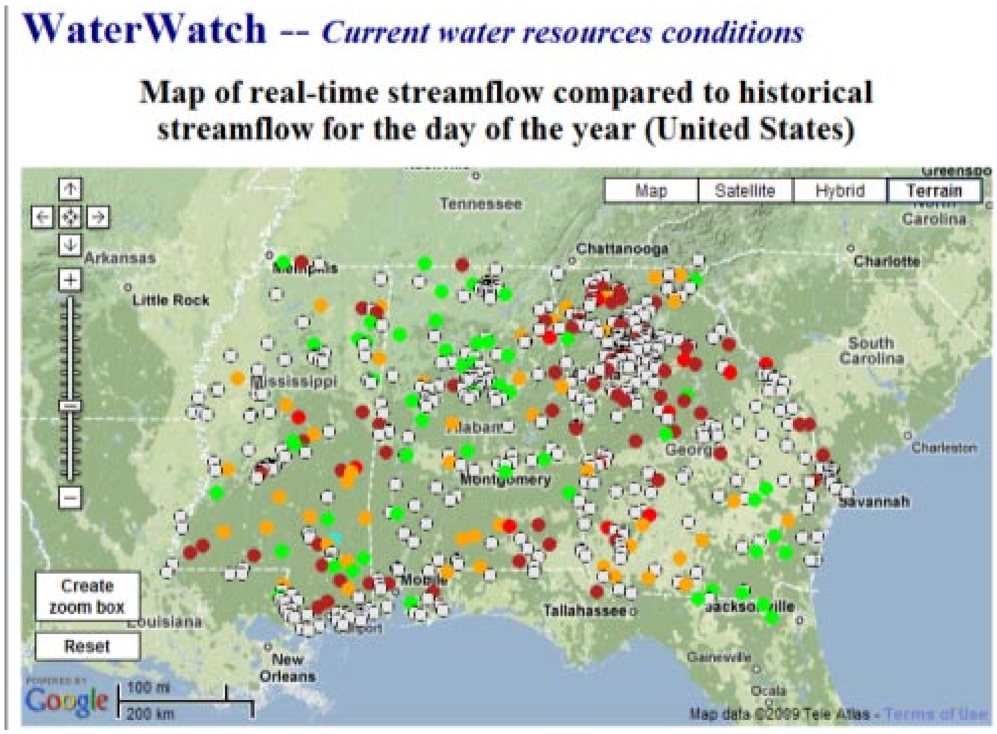

Figure 4-3. USGS-Google Earth map of real-time water data stations. (Source: USGS 2009b)

The “Models” menu on the main Sulis screen is used to display numerical models’ coverage for the aquascape and waterbodies of interest. Those models are shown in the upper right corner of Figure 4-1 and used to populate the database of results.

The three buttons on the lower right of Figure 4-2 invoke a second layer of User Interface screens for advanced visualization tools, gaming, and user-specified scenarios. The “Visualization” button on the interface opens a suite of 2-dimensional and 3-dimensional graphics tools to display spatial data that are either static or time-varying, including pan and rotate, zoom, and animation capabilities such as are available to modelers through model interfaces such as EFDC Explorer (Dynamic Solutions 2009) and the Corps’ SMS (USACE 2009c). Figure 4-4 shows sample Sulis interactive, 3D visualizations.

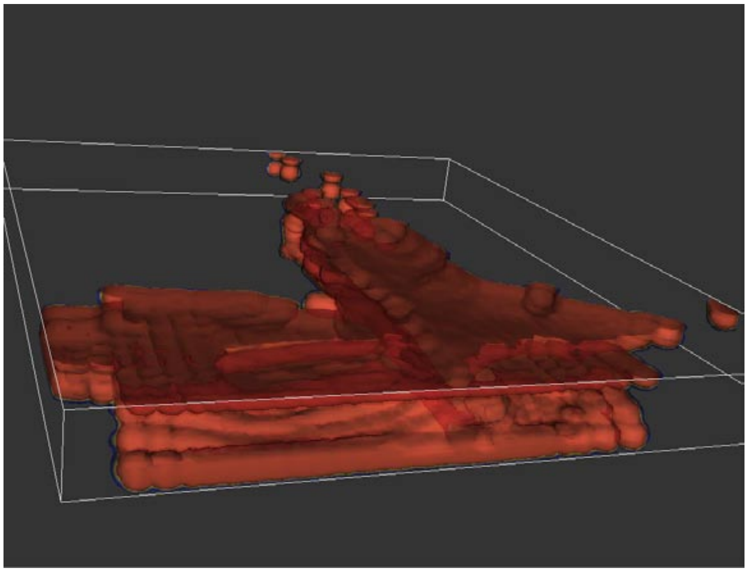

Figure 4-4a. Sample 3D volumetric display of salinity data in Mobile Bay

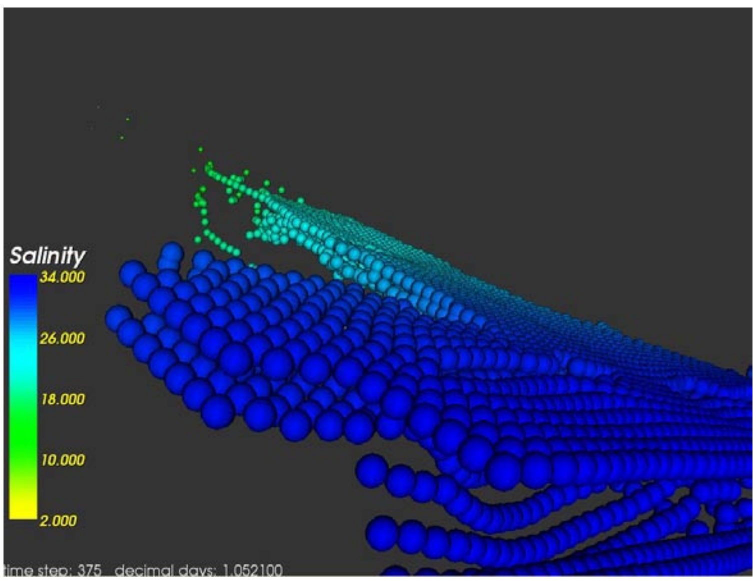

Figure 4-4b. Sample 3D “glyph” display of salinity data in Mobile Bay

Selecting the “Gaming” button on Figure 4-2 opens the serious gaming section of Sulis. A serious game refers to a “… software or hardware application developed with game technology and game design principles for a primary purpose other than pure entertainment. Serious games include games used for educational, persuasive, political, or health purposes” (Wikipedia

2009). As intended for Sulis, serious gaming will provide training for water resources professionals and students, including virtual labs for distance courses, and support brainstorming activities to solve common resource problems, such as Total Maximum Daily Load allocation exercises. The U.S. Department of Defense is using serious games technology for training and mission rehearsal, and Sulis will exploit this type of capability to train and conduct "what if" scenarios.

The "Scenario Manager" button in Figure 4-2 opens a modeling query screen in which the user poses what-if questions that typically require a prediction of conditions that have not occurred, such as surge levels along the coast during an hypothetical hurricane, streambank erosion caused by increased runoff from a proposed shopping center, or dissolved oxygen variations in a reservoir if the rule curve governing flow releases is modified. Such predictions, for which observed data do not exist, must be made using modeling technology, often sophisticated, process (e.g., physics and chemistry) based numerical models, which are discussed in Section 4.4.

An alternate mode for the Scenario Manager consists of setting goals and asking for suggested actions to achieve those goals. The Manager will then extract a list of possible measures and offer a pick list of practices from which the user selects and asks the Inference Engine to evaluate for effectiveness and cost.

4.3. Observed Data

Observed data within Sulis consist of user-specified information obtained from measurements. It includes three-dimensionally spatially distributed, time series scalar, vector, and descriptive data about land, water, and the systems affected by, and affecting water. Examples include data and metadata for:

- Wind speed and direction at multiple elevations from multiple locations at hourly intervals over weeks to years.
- Species abundance variation in space and time
- Bathymetric/hydrography/topography
- Satellite digital imagery from multiple passes
- Land use/land cover in x,y and shape file format
- Wave observations

Some data will be stored locally, such as information collected by the Sulis user and data from public databases that are used so frequently that they are downloaded once and retained.

Much data will remain on servers for downloading only when needed. Large server-housed databases accessible by Sulis include:

- U.S. Geological Survey surface and ground water data
- National Ecological Observatory Network (NEON)
- EPA Better Assessment Science Integrating Point and Nonpoint Sources (BASINS)
- National Coastal Data Development Center (NCDDC) databases

The NOAA National Coastal Data Development Center (NCDDC) provides data integration services supporting coastal marine ecosystem assessment and modeling, following a flexible, standards-based and service-oriented approach. These services, known collectively as the EcoWatch data integration framework, will be used o build integrated data access into Sulis.

4.4. Models and Model Data

We use the word “model” to label a variety of different things. We can use it to describe the occupation of a person who wears designer clothing on a fashion runway, an ideal such as “model parent,” or a small imitation of the real thing. One of us was once complimented by a student calling him a model professor, only to hear the student confide to classmates that she meant the latter definition.

Sir Peter Medawar said that the business of science is building explanatory structures, telling stories which are scrupulously tested to see if they are stories about real life.[8] We can use his insight to define a model as being *a story that describes real life*, or, more formally as *a representation of a process or thing which can be used to predict some aspect of the process or thing’s behavior.*

Neither definition requires that a model be true in the sense that is accurate in every respect. A model is successful if it describes, to an acceptable level of accuracy, those aspects of real life that we are interested in. A plastic toy airplane can tell us a lot about what a particular type of plane looks like, but nothing about how well it flies. A fashion model may tell us how skinny people look in jeans, but not how we look in those same jeans.

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[8] Paraphrased from several publications, including “Two Conceptions about Science,” in a collection of Medawar’s essays titled, *The Strange Case of the Spotted Mice*, Oxford University Press, 1996. Sir Peter won the 1960 Noble prize for his work in immune effects in skin grafts.

We can extend these definitions by qualifying them, as in:

- Conceptual Model – uses logical or relational statements to represent a process (examples: water runs downhill, oysters thrive in salty water)
- Mathematical Model – uses mathematical expressions to represent a process (examples: Newton's Second Law, Conservation of Mass)
- Numerical Model – uses numerical techniques such as approximation and iteration to obtain approximate solutions to mathematical models (examples: HSPF, HEC-RAS)

Conceptual models can be quantified, as described in Section 3.3, if needed. In studies of Mississippi River Diversions to increase oyster production in Louisiana and Mississippi, the models have sometimes consisted of the "Ford Line" which represented a target for the 15 psu[9] salinity contour and in other cases the "Soileau Line" which is an annual cycle of salinities for desirable oyster populations. In both cases fisheries biologists noted the limitations of such simple quantifications but used them to identify quantitative distinctions among multiple diversion plans.

Some mathematical models, such as Newton's Second Law, do such a good job of prediction that they earn the appellation of "law," even though they are still approximations within specific limits, as demonstrated by Albert Einstein in his Special and General Theories of Relativity. (See, for example, Hawking 1988)

Simple mathematical models, such as Manning's Equation for open channel flow, can be solved by algebraic methods. More complex models, such as the Navier-Stokes equations for flow, must be solved by numerical methods such as iteration and approximation. (See, for example, Martin and McCutcheon 1999)

In the following sections we briefly discuss how models might be used in Sulis for physical, biological , economic, and societal processes. This reductionist approach contradicts the holistic perspective we seek, but since our goal is quantitative results, we must work with the tools available, which are reductionist in nature. Figure 4-5 illustrates how wholeness of an aquascape consists of components from the five major disciplines. Sulis' Inference Engine and the GIS viewer's layering will help the user synthesize the results.

The "Models" component of Figure 4-1 consists of physical, biological, economic, and social models of the aquascape that have been created or installed during Sulis setup. They are called

[9] Practical salinity units, equivalent to the traditional parts per thousand.

models because they represent the system in a way that enables predictions to be made. Predictions may be for conditions that have not yet occurred, such as the period after removal of an existing dam or construction of an oyster reef, or to fill in details of a historical period where existing data are insufficient or missing.

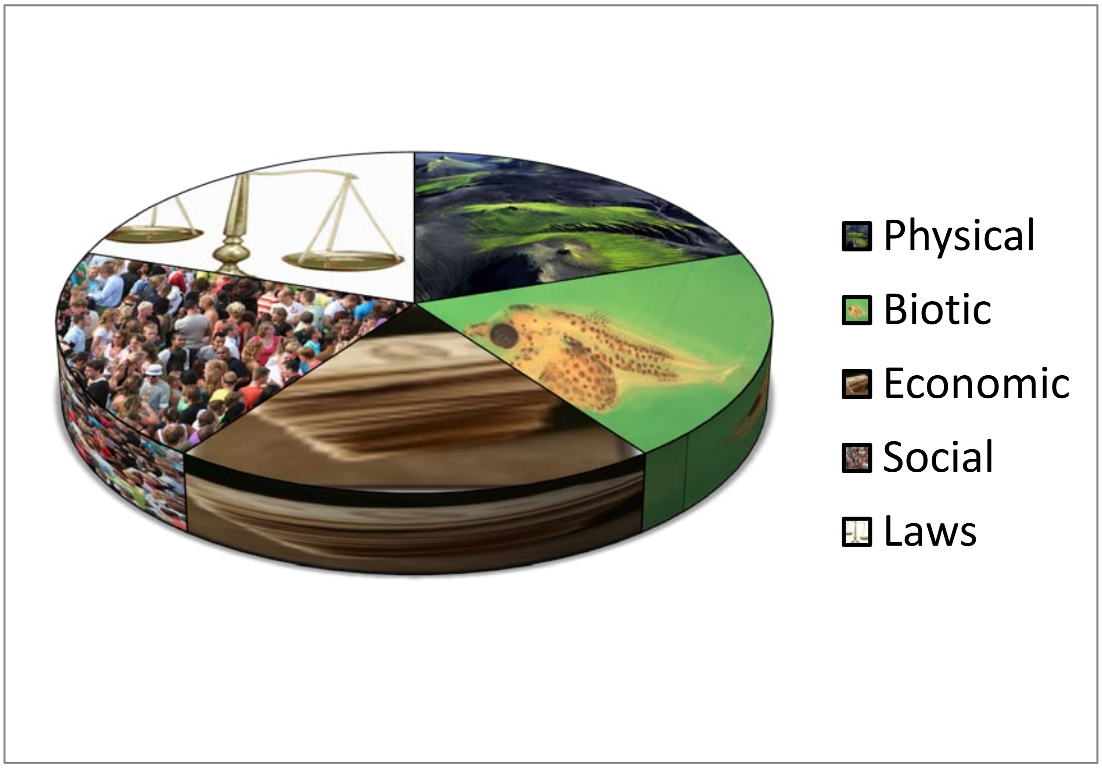

Figure 4-5. The reductionist calculations of discipline-oriented models must be brought together to show the big picture of the aquascape as a "whole."

4.4.1. Physical Process Models

Physical process models are typically mathematical models that range from relatively simple equations that can be solved algebraically to nonlinear partial differential equations that require sophisticated numerical algorithms solvable only by computers.

Algebraic solution models include simple expressions such as Manning's equation for steady, uniform flow and complex sets of equations such as Hans Einstein's sediment bedload equations. Most are strongly empirical relationships with adjustable coefficients that vary over a wide range, so their use as predictive tools require significant expertise if large errors are to be avoided. There are thousands of such models, often collected into toolkits for internal use or even sale by engineering and software companies. Federal agencies typically make their simple tools available for internet download, such as NOAA's N-Spect, cited earlier.

Numerical models are commonly used for predicting physical processes, since they rely on fewer and less variable empirical coefficients. They all require that a digital representation (or model) be constructed to characterize the size and shape of the area of interest. The digital model, commonly called a grid or mesh, contains spatial information specific to the site, such as elevation, soil type, vegetation, etc. They may consider variation in only one space dimension (a 1-D model), two dimensions (2-D model) or three dimensions (3-D). Figure 4-6 shows a simple 2-D computational mesh used in modeling water levels, flows, and transport of constituents.

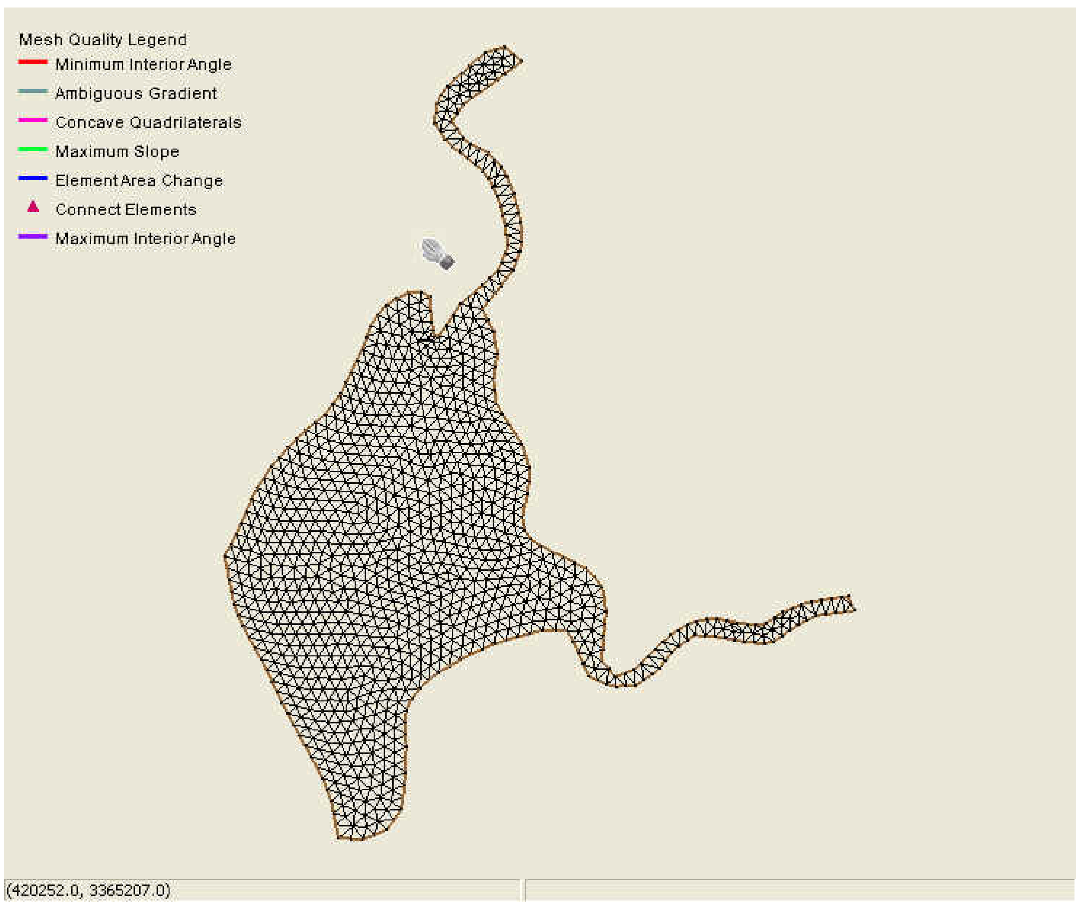

Figure 4-6. Computational mesh for a numerical model of water levels, flows, and constituent transport.

Table 4-1 lists a common classification of physical process numerical models (for a specific delta islands and levees application) into long-term climate, shorter term weather, hydrology, hydraulics, transport (sediment, pollutants, and other materials), and navigation safety and provides examples of each.

Table 4-1. Process-Based Models in Common Use (adapted from McAnally et al. 2009)

Processes	Examples
Future Climate – sea level and alterations to weather patterns	General Circulation Models, such as NOAA's GFDL
Weather – precipitation, temperature	NOAA's READY system
Hydrology – rainfall/snowmelt runoff, evapotranspiration, infiltration, groundwater	EPA's HSPF and Corps' HEC-HMS and GSSHA
Hydraulics and Sediment Transport	Corps' HEC-RAS and ADH, EPA's EFDC, and USDA's Concepts
Water Quality and Toxics Transport	EPA's WASP and Corps' ICM
Navigation Safety	Corps' Ship/Tow Simulator

Models that are strongly process-based usually make more reliable predictions than those that are strongly empirical. For example, the hydraulic models ADH and EFDC solve the fundamental three-dimensional equations of motion (conservation of mass, momentum, and energy) with only a few empirical coefficients that don't vary much, so validated simulations of future water level and flow conditions are considered rather reliable if the driving boundary conditions are accurate. On the other hand, their simulations of sediment transport employ strongly empirical equations with coefficients that can vary hugely, so results from those simulations must be highly qualified.

The down side to process-based models is that they can require substantially greater amounts of computer time, so that HSPF, a one-dimensional mostly empirical hydrologic model, runs very quickly, typically generating results within seconds; whereas GSSHA, a two-dimensional process-based hydrologic model, runs comparatively slowly, sometimes taking hours to generate results for a large watershed. For the Scenario Manager, tradeoffs between speed and reliability are handled by the Inference Engine, as discussed in Section 3.3.

4.4.2. Biological Process Models

Biological process models should provide scientifically-based insight as to how the ecosystem, and/or specific species, may respond to changes in forcings, such as flow and water quality. However, ecosystem processes are incredibly complex, requiring the holistic view espoused here. Water regime is a key driver, as it organizes the physical habitat upon which the ecosystem is structured, so any robust ecosystem model must be linked to the hydrology and hydrodynamics of the system.

Achieving accurate quantitative results from the modeling of entire ecosystems, and even specific ecological questions, is an on-going challenge. Unlike physics-based hydrologic models, there are few first principles from which to derive ecological models. General ecosystem models are not favored by many ecologists due to the necessity of large amounts of input data, over-parameterization, and the complexity of ecosystems. Such complaints are similar to those expressed in opposition to numerical hydrodynamic models in the 1960's and 1970's – they had merit at the time they were expressed, but too often were used as an excuse for not moving the technology forward by eliminating the deficiencies one at a time. Hydrodynamic modelers have overcome those deficiencies to the extent that their models are now accepted as definitive, and ecosystem models will follow that same path.

As one example of an ecosystem model that is becoming a useful tool, Ecopath is a trophic mass balance calculation which, combined with modules Ecosim and Ecospace, provides a dynamic modeling system for predicting temporal and spatial ecosystem impacts of fisheries and environmental stresses (Christensen and Walters, 2004). It provides a system-specific graphical user interface for data management. Over 100 applications of the model have been made worldwide, and the model has been coupled with the USACE water quality model CE-QUAL-ICM (Tillman et al., 2006) for application to Chesapeake Bay and is being linked with ADH to model Pool 5 of the Mississippi River. The software is distributed free by the University of British Columbia's Fishery Centre (UBC 2009).

Atlantis is a coupled biologic-oceanographic model framework providing trophic dynamics of 54 food web groups (e.g., phytoplankton, fish and zooplankton) based on nitrogen tracking. Brand et al. (2007) applied Atlantis to the California Current Ecosystem and used it to test the effects of climate-driven changes in upwelling and coastal currents.

For systems in which ecological models are not available or are not yet trusted by stakeholders, semi-quantitative criteria such as the Ford Line salinity criterion cited in Section 3.4.1, EPA's Habitat Indicators (EPA 2008), NOAA's Integrated Ecosystem Assessment (Levin et al. 2009) and Indices of Biotic Integrity (IBI) can be applied. Figure 4-7 illustrates one of the EPA indicators, that for water clarity.

Area	Good	Fair	Poor
Sites in coastal waters with naturally high turbidity	> 10% light at 1 meter	5-10% light at 1 meter	< 5% light at 1 meter
Sites in coastal waters with normal turbidity	> 20% light at 1 meter	10-20% light at 1 meter	< 10% light at 1 meter
Sites in coastal waters that support SAV	> 40% light at 1 meter	20-40% light at 1 meter	< 20% light at 1 meter

Figure 4-7. Example Semi-Quantitative Water Clarity Index (Adapted from: EPA 2008)

Index of Biological Integrity (IBI) processes have been adapted by a wide variety of agencies to aid in determining whether aquatic systems are biologically impaired. The M-BISQ methodology developed by the Mississippi Department of Environmental Quality determines aquatic health or biotic integrity based on a biological rather than chemical monitoring plan, under the assumption that biota integrate impacts. It employs five indices (one for each bioregion), each with 6 or 7 metrics, as shown in Figure 4-8.

Until quantitative ecosystem models become fully accepted, qualitative and semi-quantitative methods presently in use can constrain their results or even be implemented within the inference engine in a standalone approach through application of Bayesian Belief Nets (BBN), described in Section 3.3. For example, one of the authors participated in a study of deepening the Galveston ship channel in which fisheries experts labeled various salinity distribution changes in the Bay as either positive, negative, or neutral for several commercially important species of oysters and shrimp. The collected opinions were then synthesized to identify changes that were unambiguously good and bad for fisheries production in order to pre-screen plans before more sophisticated (and expensive) detailed evaluations were performed. Such screening level evaluations are a natural for BBN.

BIOREGIONS				
Black Belt	East	Northwest	Northeast	West
Metrics				
No. Collector taxa	% Caenidae	No. Chironomidae taxa	% Clingers	Hydropsychidae/ Trichoptera
Beck's Biotic Index	No. Tanytarsini taxa	% Clingers	% Diptera	Beck's Biotic Index
No. Plecoptera taxa	% Filterers	% Ephemeroptera (no Caenidae)	% Filterers	No. Sprawler taxa
Total taxa	Beck's Biotic Index	No. Filterer taxa	% Tanytarsini	% EPT (no Caenidae)
No. Sprawler taxa	Hilsenhoff Biotic Index	Beck's Biotic Index	Hilsenhoff Biotic Index	No. Coleoptera taxa
No. Coleoptera taxa	% EPT (no Caenidae)	Hilsenhoff Biotic Index	No. Trichoptera taxa	No. Predator taxa
% Caenidae	% Clingers	% Tanytarsini		

Figure 4-8. Mississippi Benthic Index of Stream Quality (M-BISQ) indices for macro-invertebrate IBIs by bioregion (MDEQ 2003).

4.4.3. Economic Models

Projects that require large sums of public or private funds, or combination thereof, must be carefully analyzed before monies are expended. A good capital investment has four characteristics (Beierlein et al. 2008):

- Provides a positive long-term net benefit
- When selecting among alternative capital budgeting solutions, it is the investment alternative that provides the highest long-term net benefit to the organization
- Provides benefits sooner rather than later
- Provides the lowest risk.

Construction and operation cost estimating is a well-developed discipline, with courses, textbooks, and specialized software to perform the functions. Methods to calculate other costs, such as lost opportunities costs and increased public health costs, are less well defined and are the subject of research to identify and estimate.

Some economic benefits calculation methods are well known and well documented (e.g., National Academies 2009), but others, including recreational and social cohesion benefits, are often left uncounted because of their difficulty or because they are controversial.

As might be expected, there are several methods evaluating benefits and costs to determine how to analyze long-term capital investments such as aquascapes: (1) payback period; (2) benefit-cost analysis; (3) net present value analysis (npv); (4) internal rate of return analysis; and (5) modified internal rate of return. A description of these methods is provided below.

<u>(1) The payback period</u> is the length of time it will take to generate sufficient additional cash inflows of a project to pay for it (Erickson et al. 2002). This is the simplest way of analyzing a major project that a public or private entity may want to undertake. The payback is calculated by dividing the cost of the project by the cash inflows. The payback period does not take into consideration the time value of money.

<u>(2) The traditional benefit cost analysis</u> is one of the most commonly used methods to analyze investment opportunities. Benefit-cost analysis provides a well-established framework for assessing the economic viability of a wide range of public and private sector investment strategies (Austin et al. 2007). The benefit cost ratio is obtained by dividing the estimated present value of an investment's benefits (B) by the estimated present value of costs (C) or B/C. The benefit-cost analysis framework requires that all possible benefits and costs related to the particular investment strategy be accurately estimated. This is usually not possible. For example, the inclusion of all benefits may be a utopian concept because it is extremely difficult to include all benefits in monetary terms; therefore, it might be easier to provide different ranges of values that are used as sensitivity analyses for the various strategic decisions for investment alternatives. However, it is generally much easier to estimate the costs that might be incurred on a project alternative due to the availability of monetary values on cost items. In general, if the benefits-costs ratio is greater than 1, the project is usually accepted.

The net results of the benefit-cost values aforementioned can be incorporated into an input-output model to determine how the proposed project can affect the overall economy of a local area, state, or region. The input-output model such as the IMPLAN Model has the ability to provide three types of effects measured with a multiplier: the direct, the indirect, and the induced effects. The direct effect is the known or predicted change in the local economy that is to be studied. The indirect effect is the business to business transactions required to satisfy the direct effect. Finally, the induced effect is derived from local spending on goods and services by people working to satisfy the direct and indirect effects (Minnesota IMPLAN Group 2009).

<u>3) The net present value method</u> allows a public or private entity to evaluate a major project undertaking by considering the time value of money. Essentially, it helps the entity to find the

present value in today's dollars of the future net cash flow of a project (Business Owner's Toolkit, 2009). An investment's net present value is the difference between the present value of its benefits and the present value of its costs (Beierlein et al., 2008). If the net present value of the project is positive (that is the present value of the project's benefits is greater than its present value of costs), then the project should be undertaken by the entity. The formula for calculating the net present value of a potential project is shown in Figure 4-9.

Net Present Value (NPV)

$$\text{NPV} = \sum_{t=1}^{T} \frac{\text{Cash Flow}_t}{(1+i)^t} - \text{Initial Cash Investment}$$

t = Cash Flow Period
i = Interest Rate Assumption

Figure 4-9. Net Present Value Formula (Source: MYSMP-My Stock Market Power 2009)

<u>(4) Internal rate of return analysis</u> is a variation of the Net Present Value method. The internal rate of return is the discount rate that makes the net present value of an investment's benefits equal to the net present value of its cost (Beierlein et al., 2008). Rather than applying a known discount rate, the goal is to solve for the discount rate that makes the Net Present Value equal to zero. The discount rate is estimated is the rate of return on the potential project. In general, the decision rule is to accept projects with a rate of return greater than or equal to the opportunity cost of the investment. Generally speaking, the higher a project's internal rate of return, the more desirable it is to undertake the project (Investopedia, 2009). The formula for estimating the Internal Rate of Return (IRR) is as follows (Jain and Saidha, 2009):

$$NPV = CF_0 + \frac{CF_1}{(1+IRR)} + \frac{CF_2}{(1+IRR)^2} + \frac{CF_3}{(1+IRR)^3} + \dots + \frac{CF_N}{(1+IRR)^N} = 0$$

where

IRR= Internal Rate of Return

CF_N=Net cash flow at time period N

N = number of years.

CF_0= Initial cash outlay (investment)

NPV= Net Present Value

Which can be recast with NPV and CF_0 = 0 to obtain:

$$NPV = \sum_{t=0}^{N} \left[\frac{CF_t}{(1+IRR)^t} \right] = 0$$

(5) The modified internal rate of return (MIRR) is a financial measure used to determine the attractiveness of an investment. It is generally used as part of a capital budgeting process to rank various alternative choices. As the name implies, it is a modification of the Internal Rate of Return (Wikipedia 2009b).

The modified IRR assumes that cash flows are reinvested at the company's cost of capital. The cash flows are first brought forward to their future values at the company's cost of capital. Next, the terminal value is calculated by summing all of the future value cash flows. Finally, the terminal value is brought to the present value of the initial investment at the MIRR rate (Jeffus 2009). The formula for the MIRR is as follows (Jeffus 2009):

$$NPV = \sum_{t=0}^{N} \left[\frac{\text{Cash inflow}(1+r)^{t-1}}{(1+MIRR)^t} \right] = 0$$

Present Value of Costs=Terminal Value/$(1+\text{MIRR})^N$=Present Value of Terminal Value

where

r=cost of capital

$MIRR$=Modified Internal Rate of Return

Many times policy makers use complicated decision models to evaluate the feasibility (or risks and returns) of various capital investment projects. While these models are more powerful, they are at times complicated to use and need special expertise to operate.

A well structured spreadsheet (known as Project Evaluation Model or PEM) will be developed to evaluate the feasibility of capital investments in major projects. The PEM model will use Excel spreadsheet functions to develop formulas to evaluate investments in capital projects. The PEM model will be not a "black box" but a transparent and flexible tool that may easily be used to evaluate various capital-related activities in a given area.

Since the model will use standard capital budgeting techniques to evaluate the feasibility of major improvement projects, it offers the potential to compare different and similar projects in scale and time. The user will be able to model multiple projects by simply adding the extra information for the projects. The existing capital budgeting logic in the spreadsheet would apply - no additional formulas would be needed.

Figure 4-10 shows a sample view of the project evaluation model. The worksheet will require the investment level, cost of capital, and the number of years of projected cash flow to populate the spreadsheet. The spreadsheet will then calculate the decision factors: payback, net present value, benefit cost ratio, and the internal rate of return. The PEM model will automatically be programmed with Excel formulas to calculate these decision variables. While any one of these factors may suggests a project is possible, the PEM model will require at least three of the four measures be positive before deciding that it is feasible and worth the capital investment.

	Enter input data here
Capital amount	$104,000
Discount rate (or cost of capital)	0.06
Expected life of benefits	5
Reinvestment rate of cash flow funds from the investment (borrower's cost of capital)	0.05

	Cumulative NCF			NPV	Cumulative NPV or Recovery Pay Back	BC Ratio	Pay Back	IRR	Pay Back period	Pay Back Amount
	$ 125,820			$ 80,095	$ (214,785)	0.77		23.70%	3.42	$ 21,809
	NCF	Cumulative NCF	Discount Factor	DNCF						
Year										
0	$ (104,000)	$ (104,000)	1.0000	$ (104,000.0)	$ (104,000.0)					
1	$ (4,327)	$ (108,327)	0.9434	$ (4,082.1)	$ (108,082.1)					
2	$ 37,249	$ (71,078)	0.8900	$ 33,151.5	$ (74,930.6)					
3	$ 53,898	$ (17,180)	0.8396	$ 45,253.8	$ (29,676.8)					
4	$ 65,000	$ 47,820	0.7921	$ 51,486.1	$ 21,809.3		Payback		3.42	$ 21,809
5	$ 78,000	$ 125,820	0.7473	$ 58,286.1	$ 80,095.4					

Figure 4-10. Sample View of Project Evaluation Model

Figure 4-11 shows a summary view of the project evaluation data and decision factors. No inputs are necessary for this worksheet, since all entries are automatically linked and calculated from the previous worksheet (Figure 4-14).

INPUTS			**CRITERIA**
Net Investment	$104,000		
Cost of Capital	0.06		
Length of terms (years)	5		
DECISION FACTORS			
Benefit Cost Ratio		0.77	**> 1**
Net Present Value		$ 80,095	**+**
Pay Back Period (years)		$ 3.424	**<= F8**
Internal Rate of Return (IRR)		0.2370	**> F7**
Modified Internal Rate of Return (MIRR)		0.1843	**MIRR>IRR**

Figure 4-11. Important Project Evaluation Factors

Placing an economic value on ecosystem services has proven to be difficult. Howard Odum (Odum and Odum 1976) pioneered a quantitative approach using energy flows between producers (e.g., plants) and consumers (e.g. animals) and converting energy to monetary value (25,000 calories per dollar in 1973) in order to compare alternatives and value resources. Petrolia and Kim (2009) evaluated the willingness of coastal residents to pay for barrier island restoration by comparing the “opportunity cost” of alternatives, which is a sociological queston, discussed below.

4.4.4. Social Models

Social effects predictive models are overwhelmingly qualitative, with most quantitative efforts concentrated on defining present or past conditions, such as demographic data gleaned from a census. Even with historical information, interpretation is often descriptive and qualitative. Attempts to apply standard physical sciences approaches (positivism) or formulate a comprehensive model (Standard Social Science Model) have done little to make societal predictions a standard tool.

Lack of an accepted conceptual model is understandable in a science that addresses disparate topics of culture, demography, anthropology, communications, political science, psychology, and sociology. Thus, like some ecosystem effects and aesthetic values (which are considered a social parameter here), expert analysis and Bayesian Belief Nets may be the appropriate approaches to modeling most social effects of water-related management.

There is an ample base of data on the negative social impacts of large dams (e.g. Vanclay 2009) and even irrigation projects (e.g., Oosterbaan 2009), possibly because research funds are more readily acquired for problems than for successes. However, negative impacts can also be used by social scientists in an inverse sense – project characteristics (and outcomes) that should be avoided can be expressed inversely as characteristics to be sought in a new project or improved management scheme. For example, if one irrigation project is found to be unsuccessful because farmers refused to use it, a decision support tool might recommend specific stakeholder (farmer) involvement in deciding locations, quantities, and quality of diverted water.

Positive social impact examples of proper watershed management can be obtained from the experience of the Tennessee River Valley, where the Tennessee Valley Authority's efforts contributed to improved public health, literacy, and community cohesion (Miller and Reidinger 1998). They can also be found in the operating experiences of Federal agencies, such as NOAA's Catch Shares policy, in which local decisions determine individual catch allocations (NOAA GMN 2009). Research to relate the negative and positive effects to projects and their management will provide data from which semi-quantitative measures can be derived, at least for the southeastern U.S.

One arena in which social sciences modeling is solidly quantitative is demographics. Current population data from the U.S. Census is geo-referenced to tract and block levels, allowing for a reasonably good level of spatial identification. Since the Census has a great deal of characteristic data describing populations, it is relatively straightforward, if not easy, to link population characteristics to other geo-referenced information. Also, demographers are very good at projecting future population change which are essential to posing and addressing many questions that arise in resources planning.

Laws are certainly part of the social structure; however, in aquascape management they play a different role than other societal aspects – one of constraints and mandates rather than an effect to be predicted and evaluated. Therefore, laws are treated separately in Sulis.

4.4.5. Models Development

Many of the models needed for Sulis are already available. In particular, powerful numerical models for climate, weather, hydrology, hydrodynamics, and transport, including water quality, are readily available in the public domain and only minor modifications are needed to make them suitable for Sulis use. Work is underway on development of ecosystem models and combinations of evolving models and expert opinion, perhaps through Bayesian Belief Nets (see following section), that will soon provide useful tools for Sulis incorporation.

4.5. Inference Engine

The Inference Engine in Figure 4-1 is a logic and computing module that:

- Receives user queries
- Processes those queries
- Fetches data as needed or computes results
- Evaluates requests and results for suitability
- Returns a response to the User Interface

Figures 4-12a and 4-12b illustrate the logic and flow of information in the Engine, which can be called by any of the four User Interface screens -- Query, Visualization, Gaming, and Scenario Manager. Query is executed by the information selection boxes in Figure 4-2, with "Update Map" button executing the query. Visualization, Gaming, and Scenario Manager user screens (not shown) are called by their respective buttons on Figure 4-2.

Figure 4-12a illustrates the Responder section of the Engine. It receives queries from the User Interface and checks two possible sources for a response – a request for observed data ("Where is?") searches the observed data sources and either returns the requested information or a null result; a request for a prediction ("What if?") searches the modeled data and either returns with a pre-calculated result from the database or requests a calculation ("Calculator") which generates and returns a result.

The Calculator, illustrated in Figure 4-12b, uses the model results database to create information that addresses queries. For quantitative information, it will use Model Results and employ simple tools and/or an artificial neural network (ANN) (see Section 3.3.2) to tailor those results to the user request. For qualitative information, such as desirable, neutral, or undesirable or other non-quantitative results, it will employ look-up tables of expert opinion and a Bayesian Belief Net (BNN).

Qualitative Inference Engine calculations may use look-up tables that classify certain physical changes in a semi-quantitative way, such as fuzzy values "Good," "Fair" and "Poor" after the fashion of EPA coastal condition criteria (EPA 2008). Other examples of semi-quantitative metrics include distance from population centers such as are used to classify site desirability for noisy operations, or the aesthetic appeal of free-flowing rivers versus impounded waters.

4.5.1. Bayesian Belief Networks (BBN)

For measures that are both qualitative and complicated, Bayesian Belief Networks (BBN) have proven effective. Bayesian Belief Networks (BBNs) are probabilistic knowledge based expert systems that predict the probability of an event occurring, or diagnose the most probable cause of specific problems (Sahely and Bagley 2001). BBNs are based on Bayes' Theorem, which is named after Thomas Bayes, an eighteenth century British Mathematician and Presbyterian minister, who "first used probability inductively and established a mathematical basis for probability inference" (Britannica 2004). "Bayes' Theorem provides a way to apply quantitative reasoning to what we nominally think of as 'the scientific method'" (Pezzullo 2004). BBNs have been used in many different fields of study, but have only been utilized in environmental modeling for the past several years. They allow for use of quantitative relationships typical of Bayesian analysis combined with fuzzy logic values such as warm, hot and very hot.

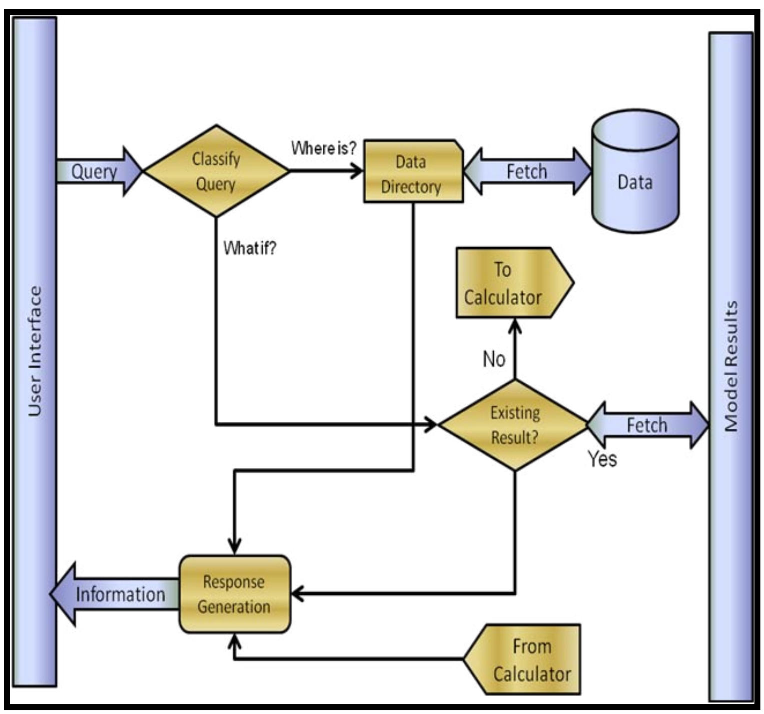

Figure 4-12a. Flow chart for Responder section of Inference Engine

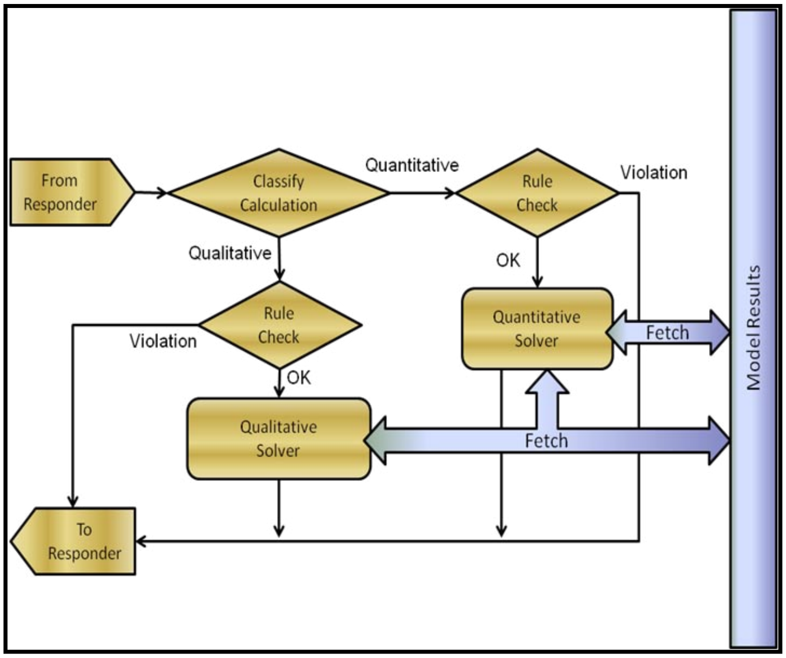

Figure 4-12b. Flow Chart for Calculator section of Inference Engine

> *The foundation of the [BBN] network is a cause and effect diagram which represents system variables as boxes and the interaction between them as arrows, the direction of which indicates the flow of cause and effect. Variables can represent anything that the user considers to be important in the environment of interest* (Cain, et al. 1999).

Many decision-makers now aim to integrate expert opinions with a GIS interface for a higher degree of data processing. BBNs have been introduced into GIS in order to incorporate statistical models and spatial explicit information. Due to GIS efficiency handling the design and analysis of spatial data and the applicability and flexibility of BBNs, it is apparent that the two create a viable spatial decision support tool capable of handling diverse data (Burrough 2001).

Figures 4-13 and 4-14 illustrate the BBN method. A cause and effect network (Figure 4-13) is constructed based on the opinion of multiple experts, who also populate the probability function of various outcomes. The probability of possible impacts can then be computed by standard statistical methods, producing tables such as Figure 4-14.

4.5.2. Artificial Neural Networks

Simple numerical models and analytic tools can be executed on a desktop computer in seconds, making real-time background simulations a possibility for Sulis. For example, a normal depth calculation for a rectangular channel executes in milliseconds and a simple HSPF hydrologic model simulation can be completed within a few seconds. However, for measures that require extensive computational effort to generate results, such as water quality changes over decades or river morphology over centuries, sophisticated numerical models may take hours to days to complete computations, far too long for an interactive decision support tool. Artificial Neural Networks (ANN) offer a short cut to obtaining such model results. This communication of information from numerical model to ANN architecture is commonly called a neuro-numerical modeling approach.

ANN are a type of biologically inspired computational model based on the functioning of the human brain. ANN are a set of real and artificial networks with the capacity to learn and adapt, generate data, and distribute processes. They are a modern computational technique for solving many complex nonlinear and dynamic problems through learning and reasoning processes.

ANN integrate sophisticated numerical modeling techniques with information sciences to create a rapid estimator relating inputs (e.g. changes in land cover) to outputs (e.g. peak runoff downstream). An ANN estimator determines the relationships among inputs and outputs by analyzing data sets derived from field observations and first principles numerical modeling and establishing complex mathematical connections among them. The process of using data to establish the connections is termed “training” the ANN.

Figure 4-15 diagrams an ANN used by NASA to predict plant outputs from inputs through a hidden layer. This diagram represents a 7 x 1 x 3 structure with 10 nodes in the hidden layer. The lines (weights) show effects of connections, including nonlinear and feedback effects.

Another example of an ANN application is given by Hsieh and Ratcliff (2009), who investigated the adequacy of a reduced set of numerical model scenario runs, from a large number of original runs, to make reliable stage-frequency estimates for hurricane storm surge. The primary tool, an ADCIRC numerical hydrodynamic model, was run on supercomputers and generated huge quantities of output data for processing. The authors used simulation results for a number of storms to train and validate an ANN which could then be used to predict storm surge elevation frequencies at just a few locations of interest.

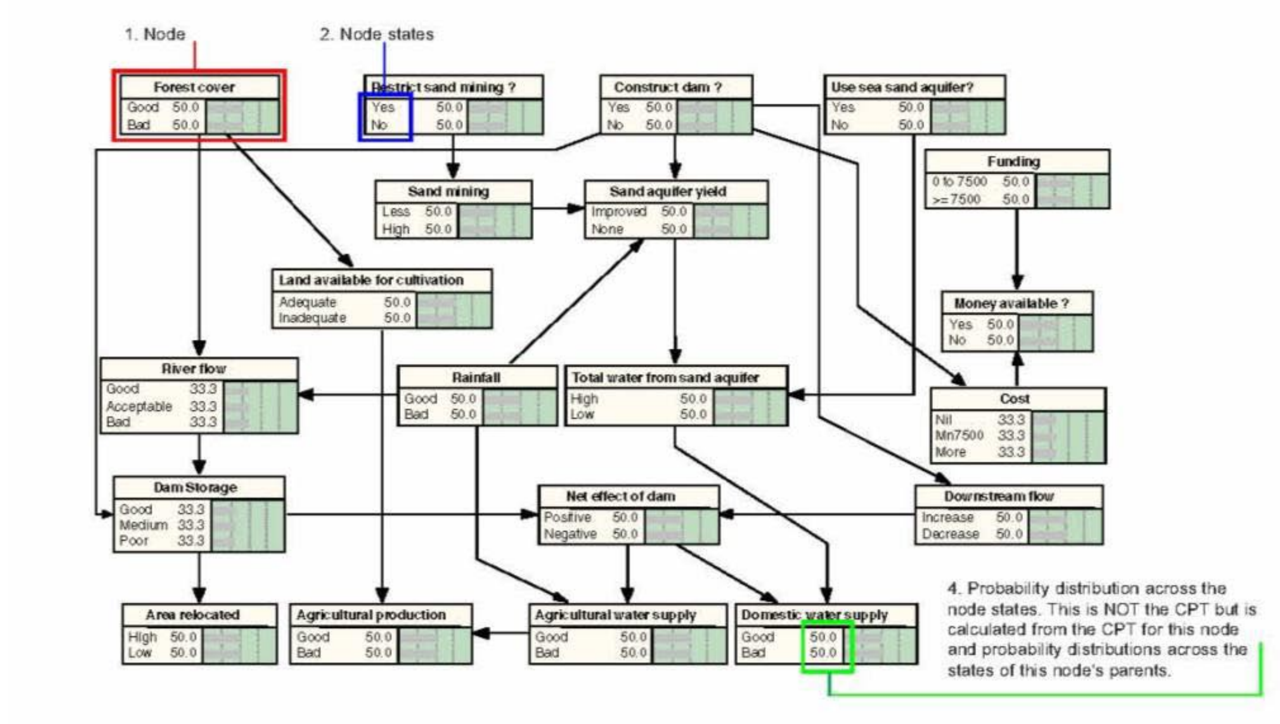

Figure 4-13. Example Bayesian Belief Network for an agricultural environmental system. Arrows indicate expected cause and effect, numbers indicate expected probabilities of outcomes. (Source: Cain 2001)

		River flow: Good	Acceptable	Bad
Forest cover:	**Rainfall:**			
Good	Good	0.60	0.40	0.00
Good	Bad	0.00	0.10	0.90
Bad	Good	0.40	0.60	0.00
Bad	Bad	0.00	0.00	1.00

Read the table one row at a time. For example, the first row says: "If forest cover is good and rainfall is good, then there is a 60% chance that river flow will be good, a 40% chance that river flow will be acceptable, and no chance that it will be bad."

Figure 4-14. A conditional probability table for the example BBN (Source: Cain 2001)

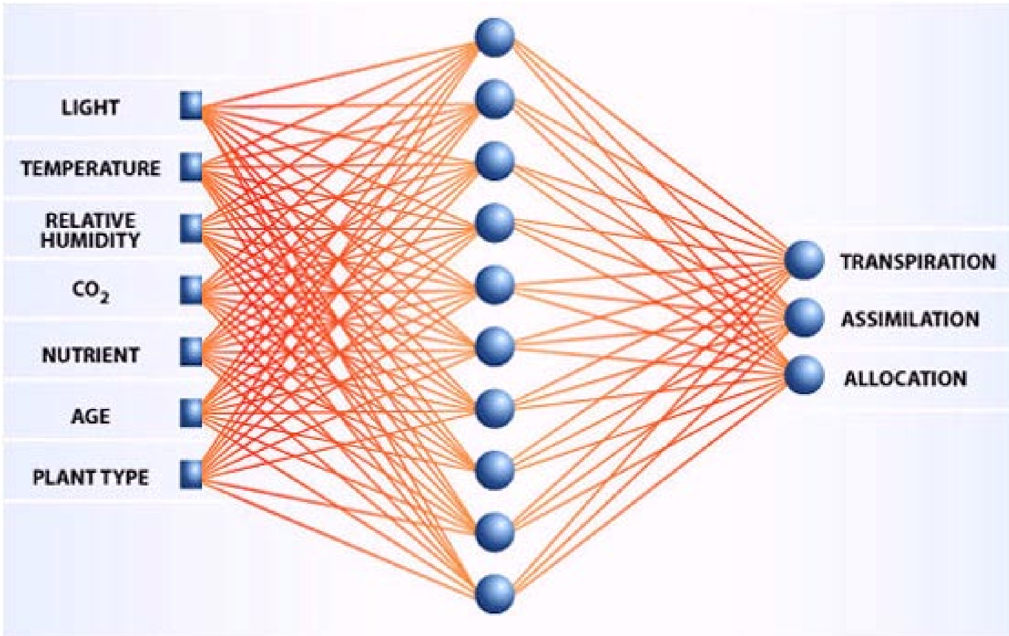

Figure 4-15. ANN diagram for plant activity (Source: NASA 2009)

As powerful as ANN techniques are, they are susceptible to misuse. One way to prevent misuse is for subject matter experts to review inputs and results for reasonableness and consistency. To augment and eventually replace expert review, we will develop and implement a principles layer to the inference engine that will include rules on model skill (error) assessment, validation range, and expected value ranges (e.g., Diaz-Ramirez et al., 2008a; Diaz-Ramirez et al., 2008b; Diaz-Ramirez 2007; Kemp et al., 2004).

4.5.3. Laws

Laws concerning water resources serve as constraints on decisions and activities. At a national level, some pertinent general laws include:

- National Environmental Policy Act of 1969, as amended, 42 U.S.C. 4321 - identified environmental protection as a major national policy objective and requires all federal agencies involved in activities or permitting of activities affecting the environment to evaluate environmental impacts and the significance of those impacts.
- Clean Water Act (Federal Water Pollution Control Act) 33 U.S.C. 1344 - forms the basis for water quality protection for surface water in streams, rivers, and lakes as well as for

groundwater. Responsibility is often delegated to states for administration and enforcement except that State laws are subject to EPA pre-emption if the state law fails to protect water quality.

- Endangered Species Act of 1973, as amended, 16 U.S.C. 1531 - the primary fish and wildlife regulatory law, designed to protect endangered and threatened species and their habitat. It is administered by the Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS).
- Fish and Wildlife Coordination Act, 16 U.S.C. 661 - requires Federal agencies to coordinate with other agencies to protect fish and wildlife.
- National Historic Preservation Act of 1966, As amended, 16 U.S.C. 470 – requires Federal agencies to foster conditions under which modern society and prehistoric and historic resources can exist in productive harmony and fulfill the social, economic, and other requirements of present and future generations.
- Estuary Protection Act- requires Federal agencies to assess the impacts of commercial and industrial developments on estuaries.
- Federal Water Project Recreation Act- declares the intent of Congress that recreation and fish and wildlife enhancement be given full consideration as purposes of Federal water development projects if non-Federal sponsors are available.
- Sustainable Fisheries Act (1996 amendments to the Magnuson-Stevens Act) – allows designation of “essential fish habitat” that requires special protection.

Other laws prescribe the activities of specific federal agencies, such as EPA, Corps of Engineers, and Fish and Wildlife Service; establish state and local constraints and mandates; and define the roles of agencies involved in all aspects of aquascape management. NOAA’s Coastal Services Support Center (CSC 2009) provides a wealth of information on laws applying to coastal and ocean waters in an atlas format. Legal information such as this is conducive to analysis by knowledge tree analysis and can be stored within Sulis’ inference engine to be displayed as reminders of what is required versus what is permitted.

5. USER INTERFACE (UI) DESIGN

Current activities focus on gathering user requirements. Specifically in this work, we are targeting the requirements of water resource decision-makers, and began with the Corps of Engineers Engineer Research and Development Center as a prototype for future involvement of other user groups.

5.1. Requirements Gathering and Design

An initial user advisory group was formed to participate in all phases of system development from requirements through testing. Formation and use of such groups is a common usability practice that involves representative users directly in requirements, and also in design through testing (Hartson and Hix 1989; Hix and Hartson 1993). The key to the value of such groups lies in their careful composition to include the appropriate users, in this case, decision makers and managers, rather than modelers.

As the initial activity in requirements gathering, the user advisory group will participate in a formal user assessment of existing decision support tools, including EPA BASINS and eCoastal. This assessment will provide metrics of the current baseline decision support capability**.**

In addition to the user assessment of existing tools, a combination of usability techniques will be employed to complete requirements gathering, including face-to-face interviews, focus groups, questionnaires, and if necessary, direct observation (Tagert et al. 2008; Rosenbaum et al. 2002).

One important output of the requirements phase will be the definition of a representative set of use cases for Sulis. Use cases provide a method for enumerating all the ways in which the user and system will interact, from the user's point of view. An example use case is given in Figure 5-1 wherein the user is attempting to determine the water supply available. Outputs from Phase 1 include:

- Requirements document for interface usability
- Representative set of use cases

USER INTENTION: findWaterAvailable

USER TASK	SYSTEM RESPONSIBILITY
T1. Specify watersheds	S1. Find watersheds
T2. Analyze measured flows	S2. Find gage data and compute statistics
T3. Decide course of action	S3. Display data sources & recommended tools
T4. Create hydrologic model condition	S4. Acquire geometric, boundary and initial condition data
T5. Render Decision	S5. Display results and recommendations

Figure 5-1. Example user-system interactions

5.2. Future Targeted Efforts: Phase 2, Iterative Design via Prototyping

In the phase following requirements gathering, prototyping of the UI and system design will begin. Prototyping is a technique essential to successful UI design, and must be done early and iteratively (Preece et al. 2002). The importance of an iterative process in which user reviews are conducted regularly throughout design cannot be overemphasized. Textual descriptions alone are insufficient for communicating with users about interface designs. Further, conventional methods typically neglect user input until late in testing when optimal UI design can no longer be achieved.

We plan to use horizontal prototyping of high level features with static electronic sketches at the beginning of the design cycle, and, in response to iterative reviews by the user group, will shift to increasingly higher fidelity, interactive prototypes towards the end of this phase (Rudd et al. 1996). Figure 5-2 shows an example of a mixed fidelity prototype screen that might be generated mid-cycle. It goes beyond an initial low fidelity sketch in showing which data to be displayed and how, e.g., layout of graphics and tables, but requires further input from users to refine issues such as color choices and specifics of text to be displayed in tables.

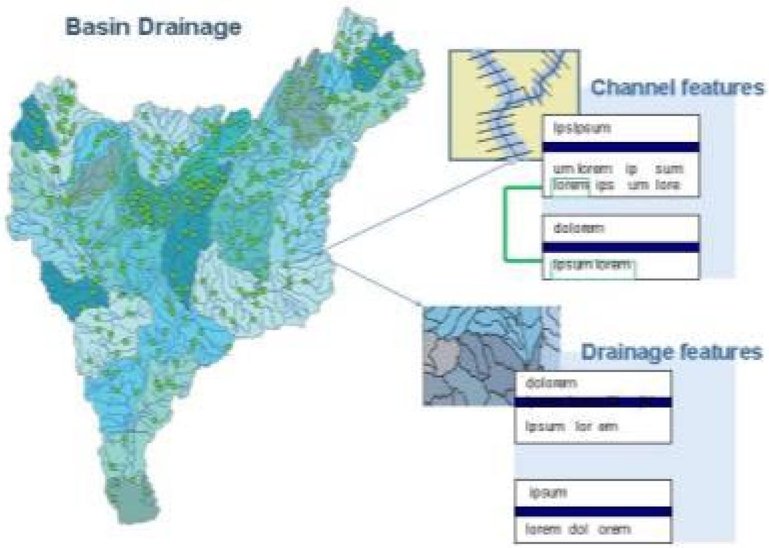

Figure 5-2. Example Mixed Fidelity Prototype Screen

6. CONCLUSION AND FUTURE ACTIVITIES

Water resource managers must make decisions with far-reaching consequences, often with poor quality or conflicting information and software tools that are directly useful only to modelers or other specialists. Developing a tool that truly meets the needs of these decision-makers requires a sound conceptual framework (holism), a modular, efficient architecture, rigorous predictive tools and an intuitive, user-oriented interface.

Water Resources is the total supply of surface and ground water suitable for use, and Water Resources Management as the process of ensuring that water of sufficient quantity and quality is available for beneficial uses. Management includes regulatory actions to conserve and protect water resources, planning to provide future resources, and actions and structures to store, divert, purify, and use water. Beneficial uses subject to management include the traditional classifications of agricultural, industrial, municipal, hydropower, navigation, and recreation plus environmental quality and habitat. It includes not only watersheds, but also coastal zones and ocean areas affected by land drainage and managed for beneficial uses, which we have defined as the aquascape. We use the phrase “Holistic Aquascape Management” to denote the practice and process of achieving sustainable water resources use for the benefit of humans and the natural environment throughout the hydrologic footprint.

This report presents a framework for a water resources managers’ decision support toolkit called Sulis, named for the Celtic goddess of wisdom. Sulis will provide users ready access to environmental and natural resources information in a useful form to better understand aquascapes and their processes, to evaluate the probable consequences of management decisions and natural change, and to make informed decisions with a holistic perspective. Healthy Watersheds – Healthy Oceans – Healthy Ecosystems, with the identifying acronym $H^{3}0$, is the underlying goal of Sulis.

We will employ a multi-phase process to ensure appropriate user involvement in design of the interface and system functionality. Past activities focused on phase 1, system architecture and gathering requirements of the target user base.

Completion of the Sulis architecture will be conducted in overlapping phases:

- User requirements gathering
- Iterative user-centered design via prototyping
- Database design and implementation
- Inference engine development
- Models development where gaps exist
- Formal system integration and testing
- User adoption and training.

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