OASIS: An Intelligent Water Management System for South Florida

Gary F. Goforth and Vinio Floris
South Florida Water Management District
P.O. Box 24680, 3301 Gun Club Road
West Palm Beach, Florida 33416-4680

Abstract. *OASIS (Operation Advisor and Simulated Intelligent System) is envisioned to be a knowledge-based advisory system for the water management operations of the South Florida Water Management District. The goals of OASIS are to help raise the average level of operational decisions made and to help preserve the knowledge used in making such decisions. The objective of OASIS Phase I was to evaluate the technical feasibility of applying AI to real-time water management. To fulfill this. objective, an OASIS prototype was developed for an area within the District limits. OASIS Phase II consists of the development and deployment of a real-time, full-scale advisory system which allows the District to leverage its water management expertise in achieving its objectives of water supply, flood control, and environmental and water quality protection. OASIS Phase II is presently being implemented over a five-year period in three stages: an intelligent warning system, a heuristic-based intelligent advisory system, and a final stage that enhances OASIS to make use of numerical models and to explore the use of model-based reasoning. Each stage will produce a useful, deployable subset of OASIS. Subsequent stages will build on the functionality of the previous stage to ultimately converge on the completed advisory system.*

The South Florida Water Management District operates more than 200 water control structures along almost 2,000 miles of primary canals within its 16,000-square-mile domain (Fig. 1). Seasonal demand for municipal and agricultural water supply, in addition to the perennial need for flood protection, environmental quality enhancement, and protection of coastal well fields from salt water intrusion, combine to create a very complex decision-making arena for the operations staff at the District. The general operating strategy is to provide adequate flood protection during the wet season (June through October) by placing water into storage and discharging excesses to the ocean, and to draw from the storage areas for water supply during the dry season. This strategy also protects the environmental and water quality values of the lakes, wetlands, and estuaries in south Florida.

General operating guidelines exist for each water control structure. Those guidelines suggest appropriate gate levels and pumping conditions for specific hydraulic objectives, including safely passing the design flood, supplying water demands during the dry season, preventing saltwater intrusion, providing flow to the Everglades National Park, and facilitating water movement and conditions during normal operations. Concurrent with the normal operating guidelines are various local operating policies which have been derived from environmental considerations, municipal and agricultural demands, and other socio-economic concerns.

To support these water control operations, the District has developed an extensive hydrometeorologic data-collection network. Real-time data are collected by field personnel, telephone-based units, and the District's microwave telemetry network, consisting of more than 650 electronic sensors located at 46 stations south of Lake Okeechobee. Sensors are automatically queried between one and four times per hour during normal operations, generating almost 65,000 records of information each day.

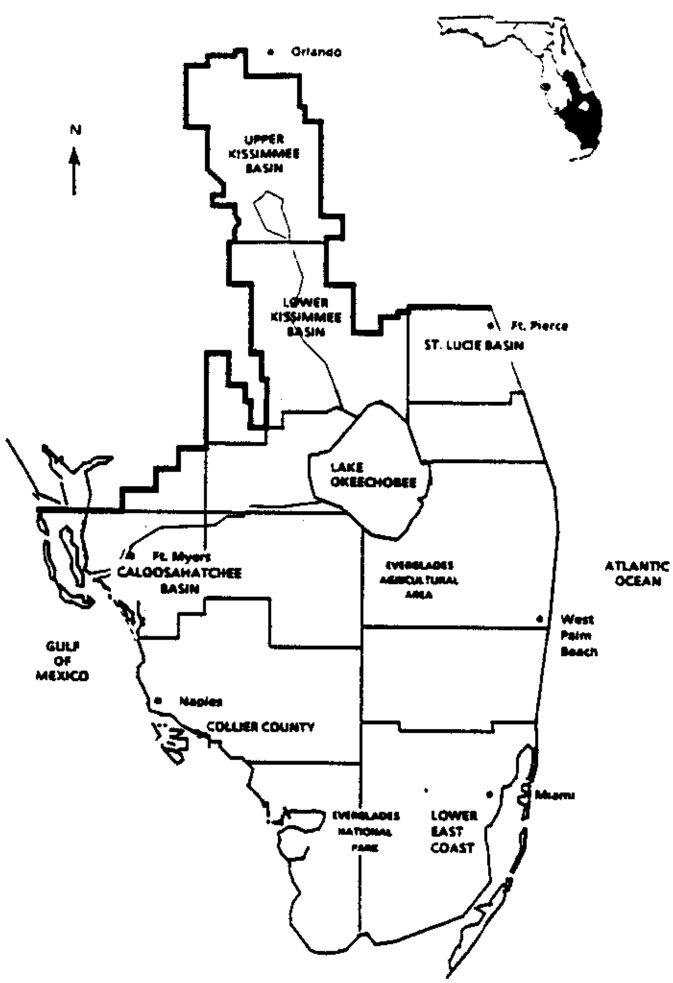

Figure 1. *South Florida Water Management District.*

In addition to scheduled acquisitions, sensors can be scanned as frequently as once per minute to monitor water operations or as checks of severe weather.

Control structure operation decisions are based on analysis of many related hydrologic and meteorologic factors; rarely are decisions based on a value of a single variable. In addition to the instantaneous water levels in canals, factors that enter the decision process include trends in the water level, local precipitation forecast, antecedent rainfall conditions, capabilities of the water control structures, information from users affected by water levels, and other site-specific operating constraints. The extensive data-acquisition program provides the decision makers with sufficiently detailed information to evaluate these factors using a combination of hydraulic operating guidelines and heuristics to determine appropriate operations.

The application of knowledge-based expert systems to the operation of the District's water control facilities was evaluated. After an analysis of operational needs and an evaluation of available technology, the Operations and Maintenance Department decided to develop and implement an intelligent real-time water management advisory system, referred to as OASIS, an acronym for the Operations Advisor and Simulated Intelligence System. Two major development phases have been identified in the evolution of OASIS: the prototype phase and the development and deployment of a full-scale water management advisory system.

Phase I: Development of an OASIS Prototype

The First Steps

Once the decision was made to proceed with OASIS, a schedule of project activities was developed. A conference was held to bring together the operations experts, control systems engineers familiar with the existing data acquisition system, potential end users, District management, and the future OASIS developers. Individuals presented their ideas of the desired goals and end products. From this session came the first comprehensive definition of what OASIS should be capable of, the specific domains of expertise to be embodied, how the advisory system should be integrated into the existing operation control center environment, what possible decision support tools should be provided, and an idea of the available data sources for the system.

Consistent with other major applications of a new technology, a reduced-scale prototype was developed to evaluate the technical feasibility of the advisory concept. The prototype concentrated on the development of OASIS features for a subset of the District's water control stations and telemetry network. The Everglades Agricultural Area is one of the 12 major hydrologic basins that comprise the District's 16,000-square-mile jurisdiction, and was selected as the prototypical region because of the variety and operational complexity of its component stations. The Everglades Agricultural Area is bounded by Lake Okeechobee on the north and three large Everglades Water Conservation Areas to the south and southeast. In all, 31 stations are located within the Everglades Agricultural Area, encompassing over 80 sensors, more than 50 control gates, and eight major pump stations located on four primary conveyance canals.

Knowledge Acquisition and Validation

The knowledge base for the District's water control operations includes both declarative and procedural information. The declarative knowledge describes static and dynamic facts and relations critical to the operation of the District's water management facilities. Static domain knowledge encompasses physical system components (e.g., canals, lakes, pumps), hydraulic characteristics, and other features that are relatively invariant over time. The dynamic component of the knowledge base includes hydrologic and meteorologic data collected in the field and transferred to the operations control center, policy decisions that influence daily operations, weather forecasts, antecedent rainfall conditions, and comments from the public. Procedural knowledge includes the hydraulic operating guidelines, empirical relationships, heuristics, operating constraints brought about by physical limits of the system, as well as fundamental domain principles, such as hydraulic relationships, and the analytical tools used by the experts to reach decisions.

Knowledge acquisition is the process of eliciting and encoding domain expertise from human experts and other knowledge sources, typically through a combination of observation, structured interviews, and research. A major challenge during the development of OASIS was to express the decision-making algorithms and procedures (that may have taken years of training and experience to acquire and utilize) in a way that was lucid enough for a non-expert to grasp. All this knowledge had to be encoded in an appropriate computer representation, and yet retain the accuracy, efficiency, consistency, and comprehensive characteristic of the domain experts.

The goals of the knowledge acquisition process were to address the following questions:

- How do the experts assess the situation?
- How do the experts define and investigate a potential problem?
- What is the appropriate strategy to solve the problem?
- What are the appropriate decision factors, and how are their values determined?
- What are the data and rules used by the experts?
- What are the tools used by the experts?
- Identify other people or agencies involved in operating decision.
- What is the time frame of the decision process?

The knowledge acquisition process began with the OASIS prototype developer becoming familiar with the domain. This was accomplished in part through observation of the experts as they evaluated situations, accessed data and relevant operating manuals, utilized appropriate analysis tools, and conferred with other individuals and agencies involved in the decision-making process. In addition, a significant amount of procedural knowledge was obtained from the hydraulic operating guidelines developed during the design and subsequent operation of the District's water control facilities. Daily operations logs, structure status information, and hourly water levels are maintained by control room personnel, providing convenient access to historic field conditions and operational activities. Additional perspectives on the decision process were obtained through discussion of the operations with individuals other than the domain experts (e.g., District management and staff of projects affected by daily operating decisions).

The second stage of knowledge acquisition was performed through the observation of the experts in action. While passive (i.e., uninterrupted) observation is suggested by some expert system developers, decisions often were based on subtle factors that required more thorough explanations by the experts. Primary facets of the decision-making process included the type and priority of data, the experts' working environment, what data are used most, with whom does the expert confer, what are the steps in the many types of operational decisions, what data format is most convenient for the expert, what type of interface capability is needed, what is the time frame for decisions, and how do the experts deal with data uncertainty (e.g., inaccurate, inconsistent, or incomplete data).

After several weeks of observation, the domain experts were formally interviewed. The interviews focused on decision factors, operating modes, data sources, and expected outcomes of operations for a prototype region of the District. Selected combinations of hydrologic and meteorologic conditions were examined. These combinations were specific enough for the experts to focus their attention, yet diverse enough to cover all practicable ranges of conditions. The main instrument used during the interviews was a matrix of decision factors, with each unique permutation specifying an appropriate set of water control operations. A challenging variety of conditions was evaluated during each interview, resulting in intense one- to three-hour sessions. During the interviews the experts collaborated for accuracy and clarity of their response. As a supplement to the experts' interviews, the daily operations logs and hourly records provided examples and further clarification of the operation rules.

Some general operating guidelines were enumerated; however, a large percentage of the water control operations depend on specific conditions and could not be generalized. The knowledge base expanded more rapidly as the general guidelines were extrapolated to undocumented operations, in contrast to incorporating specific rules with unique decision factors.

After the information obtained from these interviews was encoded, verification started with the experts evaluating the accuracy, consistency, and completeness of the OASIS knowledge base. Special attention has been given to discrepancies incurred by modeling a reduced, isolated physical area (the Everglades Agricultural Area). Conclusions of the evaluation were investigated and revisions were incorporated and subsequently re-evaluated through this iterative process.

Knowledge Representation within the OASIS Prototype

The variety and degree of expertise which compose this domain knowledge were incorporated into the data structures and procedures of the OASIS prototype through multiple knowledge representations. Declarative knowledge was represented in the OASIS prototype by means of a semantic net data structure consisting of nodes representing components in the taxonomy of the District's facilities, and links describing the nodes and their relationships to one another. Stations were defined as instances of particular station types according to their functions and capabilities. Their spatial relationship to canals, lakes, water conservation areas, and other stations were explicitly documented as slots in the station and water body schemata. Specific structures and sensors at a specific station are referenced, and each has a schema to document relevant characteristics and their current status. The dynamic information (e.g., real-time data and changes in structure status) was explicitly contained in slots of the appropriate facility schema.

The major portion of the OASIS prototype operations advisor procedural knowledge was represented by modules of condition(s)-action(s) expressions referred to as production rules. The following is a simple example:

IF all of the following conditions are met:
1. It has rained more than one inch in the preceding 24 hours;
2. The weather forecast calls for more rain;
3. The canal level has risen more than 0.25 feet in the last hour;
4. The average canal level is above 12.0 feet; and
5. A high risk of damage exists for residences in the area.

THEN perform the following action:
Investigate ways to lower the canal level.

If the conditions are met, then this rule "fires" (is executed). This action places another fact in the database, indicating that the operator is looking for ways to lower the canal level, which is subsequently compared to conditions in other rules. For example:

IF:
1. The operator is investigating ways to lower the canal;
2. Personnel are standing by at the local pump station;
3. The pumps are functional at the local pump station; and
4. There are no environmental, legal or other restrictions on pumping.

THEN: Conduct pumping operations at the local pump station in accordance with standard operating procedures.

Conflicts arose in the order that rules were slated for firing. However, as the rules were analyzed, often one or more conditions of one rule would mandate a higher priority; e.g., the risk of immediate flooding generally always carries a greater sense of urgency than the risk of reduced water supply six months from now by temporarily lowering the water level.

The knowledge base was implemented by developing rules following the top-down approach. The process starts with top-level rules which are continually expanded into more specific rules until all possible operational situations are covered. This approach provides a high degree of modularity in making maintenance much easier. Rules also interface with the schemata object-oriented data model in order to inherit attributes from objects already defined.

Access to Real-Time Data

A critical step in the development of the prototype was the interface with the extant real-time database, comprising both automated data acquisition and records of manual readings. This large existing database serves as the source of field data for the OASIS advisor. Hydrometeorological and operational data are collected on a real-time basis by a ModComp computer data acquisition system. A Micro Vax II with an Oracle database makes these data available to the OASIS prototype via a communications protocol.

OASIS Prototype Development

The OASIS prototype incorporates the dual capability of providing decision-making support to the control room operators with the supplemental ability to complete the decision process by suggesting appropriate control structure operations. The OASIS prototype incorporates four functional elements:

1. Operations Status displays real-time hydrologic, meteorologic and structural information;
2. Operations Assistant displays current and historic time series of data for trend analysis;
3. Operations Advisor is the control structure operations expert system; and
4. Alarm Status provides continuous background data analysis for detecting present and anticipated alarm conditions, complete with suggestions for ameliorating the identified alarm conditions.

The prototype was developed jointly by the District and Inference Corporation. It was implemented on a Symbolics workstation using Common LISP and Inference ART. District staff developed the conceptual design, conducted the knowledge acquisition interviews, formalized the knowledge representation, and established the communications links between the Symbolics and other computers. On a contractual basis, Inference staff encoded the functional framework, i.e., the interfaces between the different components of OASIS, prepared the initial District maps, and designed the preliminary data storage format.

The prototype is executed through a highly interactive color graphics interface that utilizes a combination of the Symbolics Lisp color system and ART's color ARTIST capabilities. A series of maps serves as the means to locate stations of interest, and screen menus are available to select OASIS functions. Desired basins, stations and operations are accessed by moving the mouse-controlled cursor arrow to the appropriate location on the screen. Keyboard interaction is required to enter some manually processed data and optional station information.

The background process within the OASIS prototype analyzes the incoming data for current or projected alarm conditions. Present trends are extrapolated for 24 hours and seven days to identify impending conditions that would require control operations. The presence of any level of alarm urgency is communicated to the control center operators through an alarm window which is present during all OASIS operations. The color of the alarm window reflects the urgency of the situation: flashing red represents conditions that require immediate attention, such as high water levels with a threat of health or economic damages; flashing yellow represents conditions that need attention soon to prevent alarm conditions that may arise within the next 24 hours; and flashing green signals the possibility that a problem may arise within the next seven days. Details of the alarm conditions are obtained by selecting the alarm window with the mouse. Suggested operations for ameliorating each alarm condition are provided upon request.

Prototype Evaluation

The OASIS prototype was deployed and used on a real-time basis in the summer of 1988. Both internal and external reviews of the prototype were initiated after its release. The evaluation effort was concentrated in system requirements, development methods, operations environment, system design, prototype implementation, and future plans. All evaluators agreed that, in general, the OASIS prototype was a successful experience and the conclusions obtained provided a good base for developing and deploying a full-scale system.

Phase II: Development and Deployment of an OASIS Advisory System

The development and deployment of OASIS full-scale system (Phase II) is based on a five-year strategic plan. The goal, at this stage, is to allow the District to leverage its water management expertise to ensure the highest level of decision-making in the short term, as well as in the long-term, horizon. OASIS enables the District to make use of levels of expertise consistently across all situations at all times and applies this valuable expertise on a real-time basis. OASIS also allows the District's water management expertise to be documented and communicated to others, allowing new personnel to be trained off-line, and helps the District rationalize decision-making and justify decisions. OASIS, as well as the Supervisory Control and Data Acquisition, the Meteorological Analysis Display and Modeling, and the Information Management System Divisional Database, are subsystems of the Consolidated Real-Time Operations System (CROS). All the subsystems mentioned above are a set of functioning components that interact in various ways.

OASIS, in support of its goals, is composed of five subsystems (Fig. 2): Intelligent Warning System, Intelligent Advisory System, Data Abstraction Management System, Maintenance and Configuration System, and Quantitative Models.

Intelligent Warning System

The primary objective of the Intelligent Warning System is to focus operator attention on potential problems. The Intelligent Warning System will perform checks consistently, vigorously, tirelessly, and quickly to identify potential abnormalities.

Both the operators and water managers continuously maintain an overall view of the status of the district operations. New data help them extend/modify their views on an incremental basis. They use predicted forecast data to mentally simulate future conditions. This enables them to identify situations that require preventive and/or remedial actions. The Intelligent Warning System will support this human activity by alerting the operator to existing and developing abnormal conditions. The Intelligent Warning System will help focus attention on abnormalities that are detected through vigorous, consistent, and rapid application of operations expertise.

Intelligent Advisory System

The primary objective of the Intelligent Advisory System is to provide solicited advice to the operator. This subsystem makes sure that the advice is consistent with existing operations guidelines formulated by the operations manager, reflects the accumulated experience in handling similar situations, and conforms with current objectives. It does these tasks quickly by consistently, rigorously, and tirelessly applying the enumerated heuristic operating expertise of the expert operators and directors.

At any given instant, operators and directors have short-term objectives for controlling the various entities within the district. These objectives are based on the existing/predicted state of the system. Operators/water managers know the repertoire of actions they can perform to control the system. They know the effect these actions will have and they can determine if they are consistent with the current tactical objectives. Finally, they use their expert judgment in selecting the appropriate action. The Intelligent Advisory System will embody such knowledge and provide it to less experienced operators (or to the experienced operators/water managers in the form of a quick reference/refresher during times of fatigue and stress).

Data Abstraction Management System

The primary objective of the Data Abstraction Management System is to provide the Intelligent Warning System and Intelligent Advisory System with a single, consistent, reliable, high-level view of data. It abstracts the underlying format, storage, communication, computation, and retrieval of data. In addition, this module is required to maintain and communicate to the CROS Information Management Subsystem the description of various entities being managed by the OASIS system, such as canals, stations, sites, and lakes.

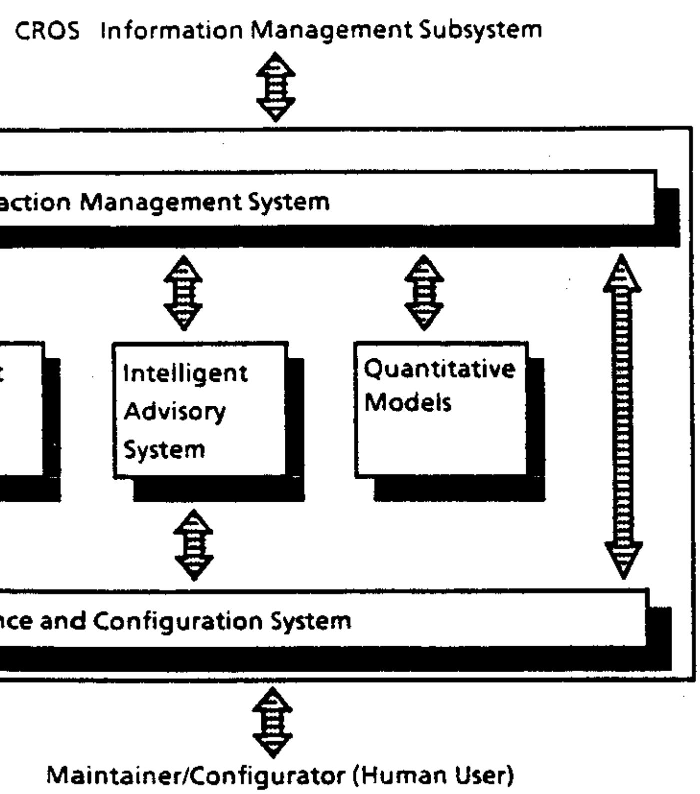

Figure 2. *OASIS subsystems.*

Maintenance and Configuration System

The very nature of expertise requires that the knowledge bases be continually updated to leverage new insights learned by the expert managers and operators. This capability enables the District to document and use its most valuable asset, operating expertise. The primary objective of the Maintenance and Configuration System is to provide the maintainer of OASIS with an intuitive user interface for modifying the underlying knowledge bases, entity descriptions, and day-to-day system configuration. In addition, the ability to quickly and easily configure OASIS to reflect existing operating conditions is key to ensuring that operators will use its results with a measure of trust essential to its long-term acceptability. The ability to edit the knowledge base is simplified by the use of a structured knowledge-base editor that is based on the problem-solving paradigm used by the water managers and operators.

Quantitative Models

Quantitative models or numerical models have been successfully applied to water management for many years. The primary objective of the numerical models is to enhance the predictive power and, correspondingly, the accuracy and richness of Intelligent Warning System and Intelligent Advisory System conclusions. Combining the use of numerical models with heuristic models for providing control advice is a powerful approach that allows the system to harness the benefits of two complementary methods of providing computer-based decision-making assistance. Using real-time numerical models can greatly enhance the ability to predict future water conditions and can prove crucial to the selection of appropriate control advice. On the other hand, heuristic representation techniques provide the best vehicle for capturing and using operator judgment of when to use such models and how to weigh the pros and cons of executing a particular control action. Numerical models will be later attached to the advisory system.

Qualitative modeling or model-based reasoning refers to generally non-quantitative causal models and not to mathematical modeling techniques. We intend to investigate and use some qualitative modeling techniques right after a major part of the heuristic system is fully operational.

At present, the Intelligent Warning System and parts of the Data Abstraction Management System and Maintenance and Configuration System are being developed at the District.

Conclusion

We conclude by reiterating three issues. First, the use of knowledge-based expert systems provides the most effective approach to leveraging the District's operating expertise in managing its decision-making process. Second, a number of benefits accrue from managing the decision-making process using OASIS. Third, the key to harnessing these benefits is for OASIS to be an integral part of the data acquisition and management systems.

One of the first questions that arises in any institution that is planning to develop a knowledge-based system is, "Will the envisioned system work for our particular situation?" The District was aided by the experience gained through the development of the OASIS prototype in answering this question by weighing the advantages and disadvantages and trying to ascertain whether the expert system option is possible, appropriate, and justified. The District's operating expertise is, to a large extent, based on heuristics that have been learned through on-the-job experience. Expert systems provide the best opportunity to document this expertise and to apply it consistently to making decisions in real-time. Thus, it is feasible to have a computer system that can mimic the experts' capacity to produce a rational and reliable decision with an explanation that is based on an effective analysis and synthesis of resource management plans and policies (given the interdependent nature of District policies and constraints.)

Experts, especially in the operation of specific water resources systems, are scarce. Their decisions, made in real-time, have a major impact on businesses and communities within the District. OASIS has the potential of managing the expertise of these experts. By explicitly documenting this expertise, OASIS can assist in the training of new operators. The highest level of documented knowledge is brought to bear on decision making at all times. OASIS helps risk management by providing a mechanism for documenting and justifying the reasons for various decisions.

Gary F. Goforth is Director of the Project Management Division, Construction Management Department at the South Florida Water Management District. He received his B.S.E. (1979), M.E. (1981), and Ph.D. (1986) in environmental engineering at the University of Florida. From 1986 to 1988 he was project manager for OASIS Phase I at the District.

Vinio Floris is a Senior Water Resources Engineer, Operations Division, Operations and Maintenance Department at the South Florida Water Management District. He holds an M.S. (1986) and a Ph.D. (1989) in civil engineering from Colorado State University. In 1986 he joined Simons and Associates, Inc., developing water resources mathematical models and knowledge-based expert systems applications. He is currently leading the OASIS Phase II project for the real-time operation of a complex water system for south Florida.