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Environmental Information Management Systems as Templates for Successful Environmental Decision Support

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Abstract: The mantra that successful Environmental Decision Support Systems (EDSS's) are those that benefit from a high level of end-user involvement during the design phase and subsequent implementation is well founded. However the practical matter of eliciting the relevant information from stakeholders to develop a useful and robust EDSS is rarely adequate and this weakness contributes to the high rate of failed EDSS's. Stakeholders sometimes have difficulty articulating the decisions they are called upon to make and cannot definitely describe the bounds of the decision space within which they operate. The EDSS developer is challenged by having to understand the system he/she is attempting to simulate to the same degree as the stakeholder. Environmental Information Management Systems (EIMS's) have a better record of success than EDSS's, though the distinction between the two is often blurry since information needs to organized and presented in an appropriate manner to inform decision making. The "handshake" between the stakeholder user of the EDSS and the EDSS itself is one of the most difficult features to determine. In the agricultural salinity management arena EDSS's do not appear to have a high rate of adoption. However there have been very successful EIMS's – some of which have user communities that number in the thousands. Perhaps the answer is to use the EIMS as a stepping stone to developing a fully functional EDSS. This paper examines a number of failed EDSS projects and compares and contrasts these systems with successful EIMS projects. The paper suggests some lessons for future EDSS initiatives.

Keywords: Environmental decision support, environmental information management systems, salinity management, water quality.

1. INTRODUCTION

There are a number of definitions of Environmental Decision Support System in the published literature – however most coalesce around the idea of using computers to support decision making. Simon (1977) – one of the early pioneers of decision science – described a systematic decision making process which he broke down into four sequential phases : intelligence, design, choice and implementation. In the intelligence phase the problem to be solved is defined, the ownership of the problem is established and essential descriptive background data is collected. In design phase a simulation model or analog that emulates the behavior of the system is developed – the model is validated during this phase and a decision framework identified. The decision framework describes the various actions the decision maker will need to choose between. The choice phase follows which identifies a proposed solution identified by the model or model framework – though this solution is not necessarily a solution to the original problem. The fourth phase is the implementation phase which applies the decision support system or modeling framework to solve the original problem.

Hence when EDSS tools fail it is important to identify the phase within which specific problems begin to surface. This is more difficult than it sounds because the same myopic thinking that led to failure of the system can prevent accurate pinpointing of the seeds of failure. This can also be a problem of perception – where two analysts, presented with the

same basic facts, nevertheless reach different conclusions. Several case studies will be examined in detail and examples of this problem will be discussed.

In business applications a distinction is made between Business Intelligence Systems (BIS) and Decision Support Systems (DSS) (Tome et al., 1977). In the business environment DSS serves as an umbrella term for groups using computers to support decision making. DSS are typically constructed to directly support decision making – the process of choosing among two or more courses of action. BIS on the other hand are geared to provide accurate and timely information – they support decision making indirectly. Interestingly most DSS are developed within academia – BIS are mostly developed by software firms for the business community. A large number of the DSS applications developed by the academic community are focused on water and environmental problems. The use of computers in DSS has facilitated faster communications, increased productivity and allowed improved data management while overcoming the cognitive limitations of human experience. However the DSS still places significant reliance on the person or people making the decision and those parties affected by the decision. This set of individuals is referred to as "the stakeholder group" and includes those actually using the computer-based DSS, those managing the application of the DSS to the problem at hand and those directly affected by the project. However a rational solution for simplified model may not be rational for the real-world problem. Understanding the mindset and function of the stakeholder group is the first hurdle in the development of a successful DSS and failure to accomplish this task is a common ingredient in DSS post-mortems. Deciding how to decide is important early accomplishment to reaching consensus. Most decision making involves a willingness to settle for a satisfactory solution (Simon, 1977) – commonly referred to as "satisficing" – where the marginal benefit of a better solution is not worth the marginal cost to obtain it.

Intuition is a critical factor used in solving many structured and unstructured problems. There is often a strong correlation between bad decisions and bad information. Decisions based on gut feelings usually have limited information. Decisions are perceived as irrational – where a decision maker may misread or miscalculate an impact or may not appreciate true risk of a wrong conclusion. Emotions can sometimes inhibit the collection of accurate data and analysis.

The case studies that follow are examples of Environmental Decision Support Systems (EDSS) whose purpose is to guide water and land resource management decisions to minimize non-point source discharges of salts and other river contaminants.

2. CASE STUDIES OF EDSS FAILURES

2.1 Natural Resources Workstation
The Natural Resources Workstation NRWS is a computer-based Unix-based integrated modeling framework designed by Colorado State University to provide wetland managers with a comprehensive tool to help guide wetland habitat restoration (Garcia and Armbruster, 1997). The impetus and funding for application of the software to San Joaquin Basin wetlands came from legal resolution of selenium toxicosis crisis at Kesterson Reservoir, where selenium tainted agricultural drainage water was implicated in the death and deformity of waterfowl embryos in wetland ponds managed by the US Fish and Wildlife Service. Tracts of agricultural land in close proximity to the reservoir was acquired by the federal government as mitigation for the land lost due to the closure of 1200 acre Kesterson Reservoir.

The NRWS is based upon a simulation model of wetland hydrology and allows the manipulation of wetland resource inputs to achieve user-defined management objectives. The NRWS graphical user interface is fully integrated with the public domain GRASS GIS system , an integrated set of programs designed to provide spatial analysis and modeling, information display, digitizing, image processing and map production support. The NRWS allows rasterized aerial photographs of each new wetland area to be combined with raster and vector maps of coverages such as vegetation cover, elevation and

irrigation suitability to be overlayed onto a base map. Critical to the application to the San Joaquin Basin wetlands is a water demand estimation component which computes the water demand per month for each of the wetland cover types based on the area of each cover type. Demand for each wetland area could be modified dynamically and a network editor used to model the surface water conveyance system that connected the diversion point with the wetland end use. The software gives the user the ability to create different scenarios, store them and compare the results using a built-in graphics package. The ultimate goal of the San Joaquin wetland application of the NRWS was to help wetland managers improve their understanding of water balances within their own wetlands and improve water management.

Although the NRWS developers spent considerable time with wetland managers that constituted their major stakeholder group ahead at the beginning of the project much of the time was spent demonstrating some of the powerful features of the software. The reception they received from the stakeholder audience during these demonstrations was very positive, despite the fact that the software only ran on a UNIX operating system, which at the time was uncommon for most water district and resource agency personnel. However the project team confused enthusiasm for the innovative visualization technology, well designed user interfaces and ability to access underlying aerial photography with enthusiasm for using the tool as an aid to decision making. In this regard the team failed the first hurdle of Simon's four part process of developing a decision support tool – that of intelligence. In this instance the stakeholder's problems were being asked to adapt to the decision tool rather than the other way around. The project team didn't develop a complete understanding of the problem that needed to be solved and the propensity of decision makers to resort to familiar tools when faced with an emergency or when under time pressure (a common occurrence in most managed wetland areas during wetland flood-up and drawdown periods).

The design, choice and implementation phases became irrelevant – though the tool had a sound design and actually did a reasonable job of simulating the hydrology of the wetland system and the flexibility of the tool made development of scenarios to choose from relatively easy. The project was implemented by conducting an intensive three day training course for the wetland Water Master at the cooperating Grassland Water District as well as agency personnel at the US Bureau of Reclamation who sponsored the study. Because the NRWS was implemented as a Unix application, an Apollo UNIX workstation with the software loaded, was loaned to the District.

The NRWS was rarely used in the first six months of deployment. After a period of weeks the training techniques learned during the training were forgotten and the opportunity to develop a routine for use of the NRWS were lost. However the NRWS never really stood a chance against the simple Excel spreadsheet the Water Master had developed himself over more than a decade to do most of his own calculations of wetland water demand and water balances. The project might have had a better conclusion had the project team started with the Water Master's spreadsheet and designed the new NRWS software tool around its basic functionality.

2.2 Watershed Management Framework (WARMF-SJR)
Salt export from agricultural, wetland and municipalities in the San Joaquin Basin is regulated as part of a comprehensive Total Maximum Daily Load (TMDL) (CEPA,2002). The TMDL is intended to identify, quantify and help control sources of pollution that affect attainment of water quality objectives in the Basin. The salinity TMDL for the San Joaquin Basin is unique in that it permitted an additional "real-time" load allocation that supercedes the conservative base non-point source load allocation , provided a real-time water quality management program is implemented in the San Joaquin Basin. The core requirements of this program include : the development of a sensor network to perform real-time monitoring of information among stakeholders from contributing watersheds; a data dissemination system for effective sharing of data among basin stakeholders to allow model forecasting of River assimilative capacity; and sanctioning by the Regional Water Quality Control Board. The impact of this additional real-time salt load allocation would be to permit significantly larger export of salt load from the watershed - helping to overcome salt

build-up within the shallow groundwater system which would ultimately degrade the groundwater resource within the Basin.

Development of a real-time water quality management system has been underway for the past five years focused on improving SJR water quality by better coordinating the discharge of salt loads from west-side San Joaquin Basin agricultural, wetland and municipal dischargers with east-side San Joaquin Basin reservoir releases and irrigation return flows that provide dilution (Quinn and Karkoski, 1989). The model chosen for decision support which involves watershed flow and water quality modeling, salt assimilative capacity forecasting in the SJR and information dissemination was the WARMF (Watershed Analysis Risk Management Framework) model (http://www.epa.gov/athens/wwqtsc/html/warmf.html) . WARMF is a publicly available, deterministic watershed model   that can used to simulate flow and water quality (Chen et al.,2001; and Herr et al., 2000). WARMF divides a river basin into interconnected compartments of land catchments, river segments, and lakes. Catchments are further subdivided into land surfaces (canopy) and soil layers, with a fluctuating groundwater table. The catchment model, driven by meteorological data, calculates soil infiltration, ET, groundwater exfiltration, surface runoff, and nonpoint source loading. River segments receive the inflows from catchments, upstream river segments, and point sources and flow in the River is routed using the kinematic wave approximation. Diverted flow is removed from rivers, and the portion used for irrigation is added to precipitation on irrigated land uses.

Walking through Simon's DSS phases the model appeared to be an appropriate "intelligent" choice for simulation of watershed hydrology and the forecasting of River flow and salinity loading. The San Joaquin Basin application of the model had been built around a simple linear input-output model of the San Joaquin River. This data-driven model performed water and salt balances every ½ mile (800 m) along the River taking into account estimated groundwater inflows and measured diversions, agricultural, municipal and wetland return flows along the 60 mile (96 km) reach. Because the previous model had been in use for over a decade the WARMF-SJR model (the application to the San Joaquin Basin) the model design found quick acceptance. The model added capability to the existing model by simulating the hydrology of the watersheds contributing to the salt loading of the River – whereas the previous model relied on static assumptions of return flows to the River. Hence the WARMF-SJR model could better simulate the impact of drought or high rainfall events than the previous data driven model. However it was in the choice phase that the use of WARMF-SJR as a EDSS may have failed.

The WARMF model has been successfully applied to various TMDL problems around the US - the modeling framework contains a consensus module to assist in the comparison of various modeled scenarios as a means of informing stakeholders and fostering agreement. This application of the WARMF model could have been successful in the San Joaquin Basin application had the model been run for a great number of potential scenarios and the results distilled into simple spreadsheets that could be displayed and manipulated in front of a stakeholder audience. There have been many examples of successful EDSS applications that have done just this – creating a simplified screening model using the results from multiple runs of complex simulation models. The screening tool (which is often just a spreadsheet) is capable of minor modification (major modifications would require a separate complex simulation model run). However in the current application of the WARMF-SJR model this step was not taken. Developing scenario runs with the model in a stakeholder environment proved difficult because of the complexity of the model and the archane design of the user interface. Despite the fact that a number of training classes had been conducted for the stakeholder community in the use of the model, that had been well attended, and the model on each attendee's laptop at the end of the training sessions – few of the stakeholders continued to use the model. Stakeholders became discouraged by the inflexibility of the model and the need for assistance for tasks beyond running of the model and obtaining model output.

The WARMF-SJR model is not currently used for performing flow and salinity forecasts as part of the implementation of a real-time water quality management program for the San

Joaquin Basin. At the present time it is uncertain whether the WARMF-SJR model will be re-vamped to serve this purpose.

2.3 Grassland Real-Time Water Quality Management
The third case study is not an instance of a failed EDSS but what might be termed a "near miss". The application is a large tract of seasonally managed wetlands within the San Joaquin Basin which drain to the San Joaquin River. These wetlands are subject to the same EPA-mandated salinity TMDL that the previous WARMF-SJR model was being applied to – though the domain of the DSS being undertaken is on a smaller scale. This case study involves the development of a flow and water quality monitoring network utilizing continuously deployed telemetered sensors within an environmental data management system YSI-ECONET. (http://www.ysieconet.com/public/WebUI/Default.aspx?hidCustomerID=99).

The Grassland Basin wetlands are located on the west-side of the San Joaquin Basin and provide food and shelter for migratory wildfowl during winter months and sport for waterfowl hunters during the annual duck season. Surface water supply to these wetlands contain salt which, when drained to the San Joaquin River during the annual drawdown period, can negatively impact water quality and cause concern to downstream agricultural riparian water diverters. Real-time water quality management has been advocated as a means of continuously matching salt loads discharged from these wetlands and with the assimilative capacity of the San Joaquin River. A GIS-based modeling effort is underway to simulate current salt loading in the State and Federal wildlife refuges and in 160 private wetlands that make up the 170,000 acre (77,000 ha) Grassland Ecological Area (Quinn and Hanna, 2003). By keeping track of wetland salt loads in each of these seasonally flooded impoundments – drainage discharge and wetland salt loading to the San Joaquin River can be more carefully regulated to match the assimilative capacity of the San Joaquin River.

In this case the intelligence and design phases of the DSS were well conceived and have proved successful in providing information on the hydrology and salt balance characteristics of these wetlands over the entire Grasslands Ecological Area. Prior to the project there was no continuous monitoring of flow or salt loading either in to or out of any of the wetland impoundments and wetland managers were unable to relate the impacts of their management actions on the wetland contribution to River salinity loading or the impacts of changed management practices on the health and sustainability of the wetland habitat. Since wetland moist soil plant species and diversity impact the use by waterfowl – any significant changes to waterfowl habitat could have long-term impacts on the function of these wetlands as habitat for migratory waterfowl and shorebirds.

The first issue that threatened to derail the EDSS related to the choice phase of the EDSS. The first four years of field experimentation with the expanding environmental sensor network and associated studies of wetland habitat response focused on a single management action – that of a delayed drawdown as a means of demonstrating the system. Delayed drawdown was a sensible management scenario for demonstration since the action of holding wetland drainage for an additional month ensured that wetland salt loads coincided with a month-long period of high flow conditions for fish migration purposes from east-side San Joaquin Basin reservoirs. These high flow releases are of Sierran water – that is of high quality that boost San Joaquin River assimilative capacity to well above the salt load contribution by Grassland Ecological Area wetlands. Although only meant as a demonstration the whole EDSS became associated with the delayed drawdown strategy and wetland managers, fearful of a perceived backdoor attempt to impose wetland management practices on their refuges and private duck clubs became politically polarized against the concept. This issue did not succeed in derailing the EDSS initiative and has been addressed through presentations, workshops and public demonstrations of the goals of the EDSS development and the fact that numerous salt load management strategies can be investigated with the current system including early drawdown – whereby an early release of wetland drainage is followed by refilling of the wetland impoundments and subsequent release during the traditional wetland drawdown period. Salt loading during this "second flush" is lower by virtue of the shorter holding period and reduced pond evaporation.

A second issue that pertains to the implementation of the EDSS concerned providing web access to preliminary real-time sensor data from the more than 50 monitoring stations that reported to the central NIVIS data server. Providing real-time access to sensor data accessible from a watershed GIS map embedded with monitoring station locations proved to be immensely popular with stakeholders and regulators alike. The ability to show each monitoring site on a Google Earth image of the surrounding wetland landscape proved especially useful to wetland managers who developed a comfort level with the data because they could "see" themselves within the EDSS. The web-accessible site also provided the ability to compare current 15 minute data between sites which provided wetland managers with a feel for differential rates of salt build-up in wetland ponds in different areas within the Grassland s Ecological Area – information that was previously unknown.

The problem that arose which threatened to compromise the integrity of the entire EDSS was related to data quality assurance. Flow meters at all of the sites had been programmed for applications that utilized the output processing capabilities of the onboard instrument software. In our application we utilized the datalogging capabilities of the YSI-ECONET wireless mesh network topology that allows "point-to-point" or "peer-to-peer" connectivity within an ad hoc, multi-hop network. YSI-ECONET comprises a mesh of Data Nodes that collect data from flow and water quality measuring sensors and Access Nodes that have the added capability of collecting data via a low power radio interface from surrounding Data Nodes. The mesh network is self-organizing and self-healing – hence loss of one or more nodes does not necessarily affect its operation. This increases the overall reliability of the system by allowing a fast local response to critical events in the rare event of a communication problem. However the issue was not one of loss of data but rather the values reported to the YSI_ECONET logger. By intercepting the raw data signal before it was post-processed we obtained total flow volume numbers that were 100 times too high (the problem was subsequently fixed in the flow monitoring system firmware). The problem was overlooked at the onset of the project but was noticed by one of the stakeholders on whose private wetland several of the monitoring stations had been located. Only the close working relationship the EDSS project cooperator allowed the problem to be recognized early and corrected. In many instances local stakeholders will develop negative impressions of an EDSS based on early flaws and these will snowball over time without feedback to the project implementers leading to ultimate failure of the system.

The desire to put preliminary data into stakeholders hands must be tempered with the requirement to perform adequate data quality assurance. Although hydrologic management tools such as AQUARIUS^{TM} and WISKI ^{TM} have been developed to assist with automated filtering and error correcting of real-time environmental data - the technology is still under development and not widely used. The Grassland EDSS development has continued despite the setbacks caused by these unintended oversights that could have condemned the project to failure. The lessons learned suggest a different strategy to EDSS development – through a greater emphasis on information management with decision support taking a back seat until the systems are better evolved, robust in their design and proven in their implementation through widespread use.

4. CASE STUDIES OF EFFECTIVE EIMS APPLICATIONS

It can be argued that Simon's suggested phased approach to DSS development and implementation can lead to an over-emphasis on the decision making capabilities over the capability of a system to provide timely and pertinent information. Since many DSS's appear to fail in the intelligence and design phases perhaps it would be better to concentrate on developing quality data in a form that stakeholders can use it and rely on stakeholders to utilize their own native decision making skills or hire those of others who share the stakeholders world view to make decisions. Two examples of this strategy are the California Irrigation Management Information System (CIMIS) and the California Data Exchange (CDEC).

4.1 California Irrigation Management Information System (CIMIS)

The first example information management system is CIMIS (wwwcimis.water.ca.gov), a 28 year-old program of the Office of Water Use Efficiency, California Department of Water Resources (DWR) that manages a network of over 120 automated weather stations in the state of California. CIMIS was developed to assist California irrigators manage their irrigation water supply more efficiently. CIMIS weather stations collect weather data every minute, calculate hourly and daily values and store them in a easily downloadable format for fast retrieval. A computer calls every station starting at midnight Pacific Standard Time (PST) and retrieves each day's data. Once the data is transmitted, the central computer analyzes it for quality, calculates reference evapotranspiration (ETo - for grass reference and ETr - for alfalfa) and other intermediate parameters, flags the data (if necessary), and stores them in the CIMIS database. Although CIMIS was initially designed to help agricultural growers the user base has expanded over the years to include local water agencies, fire fighters, air control board, pest control managers, university researchers, school teachers and students, construction engineers, consultants, hydrologists, state and federal agencies, utilities, lawyers and weather agencies. There are currently over 6000 primary registered CIMIS data users although the client list, including those using CIMIS data from primary sources is probably 4-5 times that total.

4.2 California Data Exchange System (CDEC)
CDEC (cdec.water.ca.gov) installs, maintains, and operates an extensive hydrologic data collection network including automatic snow reporting gages for the Cooperative Snow Surveys Program and precipitation and river stage sensors for flood forecasting. CDEC provides a centralized location to store and process real-time hydrologic information gathered by various cooperators throughout the State. CDEC then disseminates this information to the cooperators, public and private agencies, and news media. The data enable forecasters to prepare flood forecasts and water supply forecasts; reservoir and hydroelectric operators to schedule reservoir releases; and water suppliers to anticipate water availability. Currently, over one hundred and forty agencies provide data to CDEC and also obtain data through CDEC's cooperative hydrologic database.

5. EDSS vs EIMS

CIMIS and CDEC are examples of successful EIMS's where the emphasis has been to provide the water user community with reliable and timely access to data to support irrigated agriculture in matching crop water requirements to water supplies and to local agencies making flood management decisions during extreme weather events. In both these examples the decision making framework is left to the end user. This is a system that retains flexibility and allows the agencies to concentrate on a function they perform well. In the case of CIMIS users – many growers and landscape managers hire irrigation consultants to help with irrigation scheduling. They are hired to advise the grower or manager on when to irrigate and how much water to apply throughout the irrigation season. Consultants can also be hired to work with an individual for a specified term to train the individual how to schedule irrigations using the consultants' irrigation scheduling software. This is a highly flexible and efficient system – a consultant whose scheduling software makes poor decisions that result in poor crop conditions is soon replaced by someone who provides better service. Such a system recognizes that decision support software alone isn't sufficient to produce an optimal result – it is also how the software is used and some professional judgment that provides a filter between suggested strategies and ultimate action.

In the CDEC example the ability to customize data output from the system and automate uploading of data files into simulation models provides support to a host of situation models of varying detail and resolution. This allows the water manager or planner more time to concentrate on model output interpretation during periods when important decisions such as making flood evacuation notices or mobilizing sandbag crews must be made in a timely manner and there is little time to manipulate data inputs to decision models.

6. CONCLUSIONS

This paper has described several EDSS applications within California that have failed to achieve their initial goals and discussed some of the reasons for these failures. Using Simon's (Simon, 1997) conceptual model of the process of developing a successful DSS flaws were exposed in the intelligence, design, choice and implementation phases of the development. Using examples of successful EIMS's in California this paper makes the argument that DSS developers may be too focused on implementing a decision model rather than creating useful data acquisition and information management portals that encourage widespread use and adoption. Perhaps the fact that most EDSS's originate in academia mitigates against the slower and more incremental process of developing a broad user community capable of providing non-unique decision frameworks.

7. ACKNOWLEDGMENTS

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