21

Decision Support Systems in Water Resources Planning and Management: Stakeholder Participation and the Sustainable Path to Science-Based Decision Making

Aleix Serrat-Capdevila, Juan B. Valdes and Hoshin V. Gupta
International Center for Integrated Water Resources Management ICIWaRM-UNESCO
Department of Hydrology and Water Resources
The University of Arizona
USA

1. Introduction

This chapter will focus on decision support systems (DSS) as they relate to water resources management and planning. Water is a resource that touches and is interwoven with numerous human activities as well as the environment we live in. Its availability and beneficial use depend on the timing and manner of its arrival (rainfall intensity, rain or snow, duration, frequency), the physical setting of the region (climate and weather, topography, geology), the engineering structures in place, the environmental constraints (existing ecosystems), the legal regulatory context and institutional policies. In most contexts, cultural values and preferences are also very important. To make good decisions, it is clear that a detailed understanding of how the system works and behaves is necessary. It is equally important to understand the implications of these decisions - what consequences are likely to ripple through the interwoven system, and what parties will be affected as a result of a particular set of actions? Understanding the coupled human and physical system is essential.

In addition to looking at the evolution of decision support tools and methods for water resources management (Section 2), this chapter focuses on how integrative science and multi-resolution models provide the basis for a decision support system (Section 3), on the overall setting of the decision making process and ways in which a DSS for water resources should be developed (Section 4). We make the argument that for a DSS to be successful and informative, the process by which it is developed will be as important, or even more so, than the finished decision support tool itself. A description of successful participatory planning approaches and collaborative modeling methods is presented, as well as a comparison of several case studies. Section 5 presents an overview on how to deal with uncertainty. We present our vision to merge adaptive management, integrative modeling and stakeholder participation to face the water management challenges of the arriving future. A synthesis and future challenges are presented in the last section.

2. Background: Water resources and DSS

Traditionally, decision support systems in water resources management have been characterized by limited decision-making scope. These decision support systems have typically been based on black-box optimization models, understandable only by technical people, and developed for very specific purposes (such as reservoir and infrastructure operations, engineering designs, etc). In general, such DSSs drew from a broad set of tools aimed at informing and supporting decision making, including a) GIS and other visualization tools to better 'read' and understand data, b) tools to help understand costs and effects of construction alternatives depending on design specifications, c) operating tables or models indicating actions to perform given a set of different coexisting constraints, and d) simulations to understand consequences of different operating policies or management alternatives, among many others.

In the US, there has been a move to consider these aspects since the 19th century, but the focus has been mostly on economic impact. For example, the 1936 Flood Control Act required only that the benefit–cost analysis be positive for a plan to be deemed feasible, and subsequent documents consolidated the concept of "*contribution to national income*" as the preeminent water resources planning objective (Loucks et al, 1981). Consequently, economic objectives – measured through benefit-cost analysis – have dominated water resources planning in the United States and worldwide, during much of the past century.

During the Harvard Water Program (1955-60), academicians and senior federal and state agency employees worked together on research and training for water resource systems design and planning. One of their principal goals was to "*improve the methodology of system design in such a way that it will meet any reasonable economic objectives within reasonable institutional constraints".* In other words, they developed tools and methods which, given a planning objective, would determine what set of structural measures, operating procedures, and water allocations ('*level of development for different water uses*') would best achieve the objective. They developed the use of multi-objective optimization methods, and proposed objective functions for economic development that could also account for other important aspects. The seminal book that came out of this program (Maass et al, 1962) describes its major accomplishments. Many of its methods remain in current use today for evaluating and ranking design alternatives based on economic efficiency.

In an attempt to address some of the difficulties of assigning economic values to the broad range of possible water resources planning objectives, the US federal government adopted (in 1973) the *Principles and Standards* of the Water Resources Council (revised in 1979) making environmental quality equally important to economic development as a planning objective. Gradually, there was a transition in which benefit-cost analysis went from being the primary objective to becoming a constraint required to ensure the economic soundness of a plan, among and equal to other considerations (Loucks et al, 1981).

However, even when planners and decision-makers acknowledged the need to account for other factors beyond benefit-cost and other quantitative analysis, the planning process was almost always engineered through the lens of computer modeling, as evidenced in the following citations: "*there are two basic approaches for solving planning models: simulation and optimization*" (Loucks et al., 1981, p.21); and "*The principal way [...] to identify, predict and evaluate the impacts of alternative plans or policies is through the development and use of mathematical models*" (Loucks and da Costa, 1991, p.3).

A good representation of the state of the art in 1990 is given by the proceedings of an international workshop on DSS for water resources research and management (Loucks and de Costa, 1991). It is interesting to note that the majority of its 24 articles are focused on software structure (pre and post-processing, databases, numerical models) user interfaces and visualization of results. Beyond mentioning the necessity for dialogue with the 'model client', very few articles referred to interactions with the end users, much less the stakeholders that were to be affected by the decisions. A notable exception is an article about USACE Hydrologic Engineering Center (HEC) software products, which attributes widespread use of its products mainly to interactions with the users: it describes a problem-driven research approach that listens to the users and tries to understand their specific needs, its program to train users, and the need for long term support in model implementation and analysis.

With few exceptions, therefore, models were developed mostly in support of the tasks to be performed by planners, managers and decision-makers, and were detached or disengaged from the challenges of being a decision-maker operating within the constraints of their constituencies and their part in the decision-making process. Not surprisingly, these prescriptive models were developed by engineers and technocrats, often viewed as the only source of trusted information, and with little or no stakeholder input (Cardwell et al. 2010). Historically this has caused difficulties in the implementation of decisions, resulting in lower than expected model usefulness, and low rates of project success.

3. Integrative science and models

The traditional approaches – with their optimization algorithms and their objective functions – were unable to successfully include into their computations the variety of important factors that are important to decision makers, and in ways that are transparent to the public. Their engineering-focused methods were unable to properly assign numbers to societal preferences and environmental values. Further, they were unable to reflect the possibility of solutions involving negotiated trade-off in a transparent way. There was no mechanism for representing the values of intangible assets, essential but invaluable variables, or the long term impacts on the resources of the commons (air quality, riparian impacts, land cover and landscape values, etc.).

During the past two decades the need for holistic approaches and cross-disciplinary teams that can address complex interactions at the basin scale and can evaluate alternative futures has become increasingly more evident. Integrated Water Resources Management (IWRM) has emerged as the new paradigm for decision-making in relation to water. This approach adopts the basin scale as the natural unit enabling water issues to be considered both in their broader context and through the more focused lenses of economic efficiency, social equity and environmental sustainability. This progression towards a holistic view of water resources research and decision-making has become reflected in new initiatives and programs within funding and donor agencies, sometimes making cross-disciplinary collaboration a basic requirement.

The need to handle information from diverse physical and social datasets, and to develop holistic and integrative decision support systems, has given rise to a new type of modeling tool in water resources planning: namely '*system dynamics modeling*'. Initially developed at MIT in the late 1960's (Forrester, 1968) for economic and business applications, system dynamics platforms facilitate flexible representations of the relevant behaviors from each component of the system, and the incorporation of feedback loops. The book *Limits to Growth* is a good example of this, as it was based on a system dynamics simulation of the earth's population growth and resource use (Meadows et al., 1972). By design, they allow the decision-makers to see the entire forest through the trees, instead of getting lost in the details of each field and its specialized models. By including only what is important from each component of the system, they make it easier to represent and gain understanding of interactions among the different components of the system.

Everyone will agree this is a complex task. If a functional holistic and integrative model is to be developed to support decision-making, it is likely that this model will draw from findings and information from models specific to each system component. Regarding natural processes from the physical system, it will benefit from more spatially explicit and detailed models. Such a multi-resolution integrated modeling approach may be essential to face multi-disciplinary research and management challenges. Models of different resolutions will allow representation of different aspects of the problem and can be geared to answer different research questions and inform different sets of decisions (Liu et al 2008). For example, high resolution models (~100m grid cells) can represent in great detail the processes in the physical environment such as the land-atmosphere partitioning of water, the role of vegetation, the interactions between surface and groundwater hydrology or the dynamics of the saline wedge in coastal systems. These fine resolution models provide the state-of-the-art scientific understanding of the physical system. They allow us to extract the key aspects regarding the functioning of the physical system to be included in the medium resolution models (~1-12 km). Models at medium resolution combine (1) a less complex but accurate representation of the natural environment and (2) the human interventions on the environment such as land use management, engineering infrastructure and its operation in terms of intercepting and moving water within the basin. These medium resolution models allow us to represent the water allocations and re-distribution within the system and bridge the gap with the coarse resolution models. The higher level (coarse) models are the best attempt to represent the socio-economic and institutional aspects of water management over a simplified representation of the natural and engineered system, with a resolution at the scale of the sub-watershed.

Besides being able to answer different kinds of research questions, the benefit of a multiple resolution modeling approach is that information and findings can be transferred - and used to fine-tune - across models. While information regarding natural processes, impacts and feedbacks in the natural system can be up-scaled from the fine resolution to higher-level models, the behaviors and policies from the socio-economic and institutional models can be used to drive lower resolution models and assess impacts on the natural system. This approach has been formulated and described in detail by Wagener et al (2005) and Liu et al (2008) based on the experience of the NSF Science and Technology Center SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) in conducting integrated multidisciplinary research addressing water management challenges in the US southwest.

Ultimately, planners and decision-makers are likely to use the modeling tools that simulate the overall behavior of the basin with a simplified but still accurate representation of all its components. Such a tool will represent the relevant behaviors of the system to answer their specific management questions. Because it draws from the findings of more complex models, this DSS model will be more computationally efficient, allowing numerous model runs in a short time. Roach and Tidwell (2009) and Kang and Lansey (2011) are excellent examples. The possibility of comparing simulations of different management options and decision alternatives through a user interface in a short time span makes system dynamics a very user-friendly DSS tool for decision-makers and the public. Indeed, system dynamics DSS have recently been used to support basin scale mid and long range planning, and management (Tidwell et al. 2004; Yalcin and Lansey. 2004; Kang and Lansey, 2011). Two integrative system dynamics case studies to support planning and decision making can be found in the Middle Rio Grande in New Mexico, and in The Upper San Pedro River in Arizona. Both basins face severe water management challenges and need to find solutions to balance existing human and environmental demands with existing water supply.

In the Upper San Pedro, where human extractions from the basin aquifer threaten a Riparian Natural Conservation Area (SPRNCA), a mandate was passed by the U.S. Congress summoning the agencies and stakeholders in the basin to find a sustainable solution by 2011. In addition to the mandate, the possibility of the main economic motor of the basin (Fort Huachuca, a military base) being moved to another region if the water sustainability problems weren't solved, was a strong incentive to act. The development of the DSS by faculty and students at The University of Arizona benefitted from strong science contributions and the collaboration with numerous local stakeholders and agencies conducting research in the basin. The model allows users to select different packages of water conservation measures to be implemented through time and space in the basin. After each simulation, estimates are obtained regarding the impacts and improvements of the selected measures on the water budget, groundwater levels in key locations, and other parameters such as the costs of implementing such measures. The model is able to represent impacts on the groundwater system and the riparian area that depend on socio-economic profile for the basin and on the water conservation measures applied by the user. Linearized relationships between groundwater pumping and aquifer water levels were derived from a state-of-the-art groundwater model of the basin – a detailed physical model with higher spatial resolution – and included in the DSS for computational efficiency. The interested reader will find detailed information of the development of the San Pedro basin DSS model in Yalcin and Lansey (2004) and in Kang and Lansey (2011).

The Middle Rio Grande DSS model, developed by Sandia National Labs in collaboration with The University of Arizona, also benefitted from multi-resolution modeling. However the inclusion of information from detailed physical models was done differently. From a detailed high-resolution hydrologic model of the basin, a simplified one was derived lumping cells with similar attributes and hydraulic behavior. From a complex model with more than 100,000 cells, a simple one was produced with only 51 compartments (~cells) and sufficient accuracy to capture the overall behavior of the complex model, thus providing estimates at a level useful for policy analysis (Roach and Tidwell, 2009). As expressed by Passell et al (2003): "*this systems-level planning model draws heavily on the inferences and results of many other more sophisticated models focused on particular aspects of the basin*".

4. The sustainable path bridging science and decision-making

In general, scientists, academicians and some practitioners are convinced that numerical models are indeed a good tool to support decision-making, but the reality is that the adoption of modeling tools by policy and decision-makers is not standard practice. The main reason behind this fact is that, being extremely busy; managers, policy-makers and elected representatives are unlikely to use a model or tool they are unfamiliar with, regardless of how good it may be. Further, they will generally not use such models if they don't feel they understand how the models have been developed, and in what ways the model has been designed to help them make informed decisions. Further, any decisions based on information provided by the models will not be considered sufficiently trustworthy if the models are perceived by the stakeholders as a) not being transparent, and/or b) if they are not convinced the model addresses their views and concerns, and/or c) their input has not been requested or integrated into the development of the model.

So, how can we merge the science, data and models with decision-making at different levels of operations, policy and governance, in a sustainable way over the long term? For all the integrative science described in the previous chapter to be perceived as credible, relevant and transparent (Liu et al 2008; Gupta et al 2011) – thus acceptable to inform and guide decision-making in the public eye – one key factor is essential: stakeholder participation through science-fed collaborative processes. In a participatory planning process, technical models used to support planning and decision-making are developed collaboratively. That is, decisions embedded in models are a product of agreement – sometimes after extensive discussion – between scientists and stakeholders during periodic meetings. Such model development forces the individuals involved to focus their communication on important issues, ranging from processes and features represented in the model, to assumptions, conservation measures, alternative scenarios, etc. This process provides an excellent setting for ongoing simultaneous discussions about specific issues, being key to a better understanding of the overall behavior of a system, the nature of certain problems and potential solutions. Importantly, the participants educate each other, and a better overall understanding is gained at many levels. First, it helps stakeholders understand the physical system, and in particular the spatial distributions of pumping, diversions and land-use management impacts in the basin. Second, such participatory processes allow for a better understanding of the drivers and constraints of each stakeholder, of the agencies and institutions being represented, i.e. what limits exist on each stakeholder's range of action. In this way, stakeholders can gain insights into the bases for their divergent viewpoints, and through increased understanding, be able to identify potential strategies to negotiate trade-offs between opposing groups.

4.1 The conceptual model: A common understanding of how the system works

One of the essential steps sometimes underestimated in the collaborative development of a model is the description and agreement on a common conceptual model of the system (Gupta et al 2011). A conceptual model of a system is the understanding of how it works and how the different components of the system interact with each other. Individuals – and especially those of us who are scientists and academicians –may often think we understand the overall system enough to develop a software model ourselves. However, our views and understanding of the system, as those of any stakeholder or individual involved in the process, are likely to be incomplete and conditioned by our background and our limited individual experience. In a collaborative and participatory process, with representation from all relevant stakeholders, all of these partial conceptual models will be shared and put in common as pieces of a collective conceptual model. Through these interactions, individual stakeholders will go through a process that has been termed *social learning* by improving their own understanding of the socio-ecological system. As the collective conceptual model becomes the basis on which decisions will be made, *sustainability learning* is the process by which actors gain shared understanding of what decisions are likely to be sustainable and which ones are not (Pahl-Wostl et al., 2007).

For the collaborative planning process to succeed it is important that everyone's partial views and understanding of the system contribute to the overall conceptual model of the system. There are currently no formalized approaches to ensure this is done properly as an initial stage. Physical scientists and modelers have often overlooked or failed to acknowledge that an effective facilitation of such stakeholder process can be challenging and falls within the domain of the human sciences practitioner. Drawing from applied anthropology, we propose a method that helps structure stakeholder participation for shaping a collective, agreed-upon conceptual model.

The Participatory Rapid Assessment (PRA, Chambers, 1994) process provides an environment wherein facilitators can pose questions or raise issues and allow stakeholders to appropriate and discuss them, expressing themselves in ways they feel more comfortable with. The efficacy of PRA can benefit from the use of tools (maps, diagrams, timelines) that help to focus discussions in which participants can contribute their information, perspectives and understanding of the reality. For example, participatory mapping, where participants can publicly draw upon their understanding of land use and water use practices, as well as the spatial linkages of water allocation in a basin, will be very visual and address potential misunderstandings in a display of social interactions. Diagrams can be of uttermost importance to learn about feedbacks across fields of study (water availability, crop production, economy) in the basin, social relationships, and vulnerabilities. The use of timelines will help understand how changes have been taking place in different areas across the watershed. The use of these tools will help develop a common conceptual model of the physical and social-economic system of the basin in an open and collaborative way. All participants will learn and benefit from this method, as long as it is properly facilitated.

If the decision-making process is to be truly coupled – including physical and human considerations - it has to look into the impacts on populations; both on economic activities and shifts in vulnerabilities. A holistic decision support system approach should seek to provide insights on different forcings in the basin, including the effects of globalization (social, economic, and environmental impacts), local manifestations of climate change impacts, and their joint effects, what O'Brien and Leichenko (2000) termed *double exposure*. To address such issues, linkages techniques such as Venn diagrams may show which external drivers may be at play in the basin and how they impact the basin system. Diagrams can show how communities see themselves integrated within the global world, their relationship with outside influences, as well as provide insights on how to become less vulnerable to external drivers.

A collectively agreed-upon conceptual model of the physical and human system of the basin will help stakeholders and decision-makers understand what are the main issues and challenges, at the basin scale and for each stakeholder. The process of putting in common everyone's understanding of the system (i.e. conceptual model) may enlighten some cause-effect relationships, as well as make evident which ones are not well understood, making evident where the uncertainties and the unknowns are in the system. These steps are essential to formulate the questions that need an answer to move forward any decision-making processes. What do we know now and what do we need to know in order to make informed decisions? Once the key questions that need to be answered have been formulated, then considerations on what type of modeling tools and decision-support systems can be pursued.

If stakeholders and decision-makers are involved in the process of developing a collective conceptual model (or shared understanding) of how the system works and what are the main issues and unknowns that need to be answered in order to make planning or management decisions, they will likely support and invest themselves in a planning process involving the development of computer models and decision support tools.

In addition, models developed in a participatory way provide a commonly agreed upon representation of a system and its problems (Lynam et al., 2002). They become an image of the common understanding that, although imperfect, can be changed and improved with time. The participatory analysis during model development, and its contribution to decision making, brings with it the necessary social learning that can alter and inform perceptions of local problems and their cause–effect relationships.

4.2 DSS models in the middle rio grande (NM) and upper san pedro river (AZ)

In the Middle Rio Grande and the Upper San Pedro River, both DSS were developed in collaboration with stakeholder groups within the setting of an open and participatory process to solve management problems.

Following a state-wide water planning process in New Mexico, a voluntary group composed of diverse stakeholder representatives from the Middle Rio Grande planning region, and called the Middle Rio Grande Water Assembly (MRGWA) was the entity responsible for the planning. Composed of five groups focusing on agriculture, environment, urban development, water management and special technical issues, the MRGWA started a public consultation process through monthly and quarterly meetings that finally produced five scenarios or tentative management plans for the region. These scenarios comprised different sets and combinations of 44 water management alternatives identified by the public during the initial consultation processes. The quantifiable alternatives were included in the Middle Rio Grande DSS model, which allowed a quantitative comparison of the water conservation alternatives. At the end, the five scenarios were combined to form a "preferred management plan" by the MRGWA, in close collaboration with the Middle Rio Grande Council of Governments (MRGCOG), representing the local governments that would be responsible for implementing the final plan. Besides helping planners (MRGWA) and decision-makers (MRGCOG) to compare and evaluate alternatives proposed by the public, the model was instrumental to familiarize and engage the public itself in the planning process (Passell et al., 2003).

In the case of the Upper San Pedro basin, the Upper San Pedro Partnership was created to solve the management challenge in the basin and close the gap between human demand, natural availability and environmental needs. The USPP is also an organization composed by stakeholder representatives from 21 state and federal agencies as well as other entities and user groups, functioning at a voluntary basis. It is structured in three main committees: the Partnership Advisory Committee (PAC), the Executive Committee (EC) and the Technical Committee (TC). The PAC is the decision making body representing all entities; the EC represents the member entities that finance projects and operations; and the TC coordinates technical and scientific advice and oversight. Composed by representatives with technical and scientific profiles from the member entities of the USPP and the modelers from the University of Arizona, the TC reports to the PAC, so that decision-making can be science-based. The DSS model was developed through monthly open meetings with the Technical Committee, where other stakeholders and the public could participate. Representatives in the TC had to agree and decide on alternatives and conservation measures to be included in the model, as well as underlying assumptions, how to deal with uncertain parameters and how model results should be displayed and visualized. At every meeting, the modeler would present the inclusion of last meeting's decisions into the DSS model, review them with the group and discuss the next steps of model construction, making it a collaborative, participatory and transparent endeavor (Serrat-Capdevila et al., 2009).

The Cooperative Modeling Group in the Upper Rio Grande is the equivalent to the Technical Committee in the Upper San Pedro. In both settings, these technical groups were in charge of developing and synthesizing the technical and scientific information that would be the basis of the planning process, working with the DSS model development, and other related tasks. In both cases, there was an effort to build public confidence and trust in the planning model (it properly addressed the issues at hand) as well as a sense of ownership (the model and the management alternatives were distilled from everyone's concerns and views).

Although the planning processes in the Rio Grande and the San Pedro River are the result of different institutional drivers (Statewide planning initiative in NM vs. basin initiative to meet a federal mandate in the San Pedro), the planning is structured around parallel organizations with similar roles. Although neither the MRGWA nor the USPP have any powers to impose policies or have any decision-making status, their individual member entities may have such powers within their particular jurisdictions. The understanding that comes from having to work together within a collaborative setting is key to influencing each other's work in terms of what actions are or are not sustainable or convenient. Most importantly, these planning and decision-support processes provide the opportunity to engage both the public and the actual decision-makers well before decisions need to be made. Thus the process itself, even long before the completion of the DSS product, will likely have significant positive contributions, and the way it is conducted will have important implications. The understanding of the physical system, of what is or not convenient for the common good, and of other stakeholders' needs and concerns can facilitate the finding of tradeoff solutions among competing needs.

For the interested reader, Serrat-Capdevila et al. (2009) provides an analysis of the lessons learned and the contributions of the participatory process by which the DSS model in the San Pedro basin was developed. Cockerill et al. (2006) presents the feedbacks from the Cooperative Modeling Team in the Upper Rio Grande.

4.3 Shared vision planning

There have been many efforts from varying perspectives to establish a methodological framework for science-based collaborative planning and decision-making. Liu et al. (2008) present an excellent study of integrated modeling to support natural resource management. Their work is presented from an academic perspective and a desire to improve the credibility, legitimacy and saliency of scientific information so that decision-makers use it. They frame their work within the setting of participatory processes but focus their efforts on the contributions of an integrative modeling approach. Mahmoud et al. (2009) has a broader scope, placing integrative modeling approaches as a tool to support scenario development for decision making. They emphasize the need for stakeholder input in order for the scenario analysis to be useful to decision-making.

Perhaps the most widely used participatory planning methodology in the US has been Shared Vision Planning (SVP). The main difference with respect to Liu et al. (2008) and

Mahmoud et al. (2009) is that SVP was developed and refined by planning practitioners that needed to solve planning challenges in their professional life. Authorized by the US Congress and motivated by the 1988 drought, the method initially appeared as the Drought Preparedness Study (Werrick and Whipple, 1994) with the goal of finding better ways to manage water during drought. The report is based on the joint effort of over 100 practitioners and researchers on how to approach water management issues in many case studies across the country during drought. The report highlights that drought responses are primarily behavioral and "*their success depends on people understanding their role, and knowing how their actions fit in a larger response*". It also states that planning will be much more effective if it benefits from collaboration between government agencies and stakeholders. This will provide easy access to insights and knowledge from the stakeholders (integrative plans), they will learn about the broader picture (social learning, understanding), thus being less vulnerable themselves, and will ensure public support for any potential water management plans (credibility and trust). The Drought Preparedness Study presented a methodology to set up a functional and integrated multi-stakeholder process to find planning solutions in the face of droughts, but can be used in any water management issues. The full report is available online at: http://www.iwr.usace.army.mil/docs/iwrreports /94nds8.pdf

Since its initial development, the method has been adopted by the US Army Corps of Engineers in many conflict resolution efforts in US water management regional disputes, and is commonly known now as Shared Vision Planning (SVP). SVP is based on three principles: (1) traditional and time tested planning methods and techniques (such as described in chapter 2); (2) structured public participation; and (3) use of computer models collaboratively developed in order to support the participatory planning process (Cardwell et al., 2009).

To efficiently benefit from stakeholder participation, SVP uses Circles of Influence as a way to structure involvement and engage stakeholders depending on their role in the process. As shown in Figure 1, participants can fall in Circles A, B, C or D, ideally representing the following:

Circle A: Planners and model developers. Their task is to integrate the work of others to develop planning alternatives and modeling tools to help decision-making. They form the core planning team that facilitates communication across the different circles.

Circle B: Stakeholder representatives and technical experts. Sometimes organized around working groups on specific issues, they provide information, insights and advice. They validate the work of Circle A and can evaluate proposed plans.

Circle C: The general public, whose members should have representatives in Circle B. A mechanism should exist to inform them and allow their feedback regarding the work of Circles A and B.

Circle D: The decision makers. Those who will ultimately decide what decisions are taken and what plans are implemented. They should be identified and actively engaged along the planning process, so they can provide feedback and guidance to the process.

These circles of influence are relatively natural, and they can be well illustrated by the case studies in the Rio Grande and the San Pedro basin, with slight differences. The Cooperative Modeling Team in the Middle Rio Grande and the Technical Committee of the Upper San Pedro Partnership would compose Circle A, the hands-on planners, in each basin. The Middle Rio Grande Water Assembly and the Upper San Pedro Partnership as stakeholder consortiums as a whole would compose Circle B, providing information to Circle A and validating its progress. Circle C is the general public in both cases. Finally, the Middle Rio Grande Council of Governments and the Partnership Advisory Committee would compose the cores of Circle D in each basin, with the possibility of other decision-making agents existing beyond those groups.

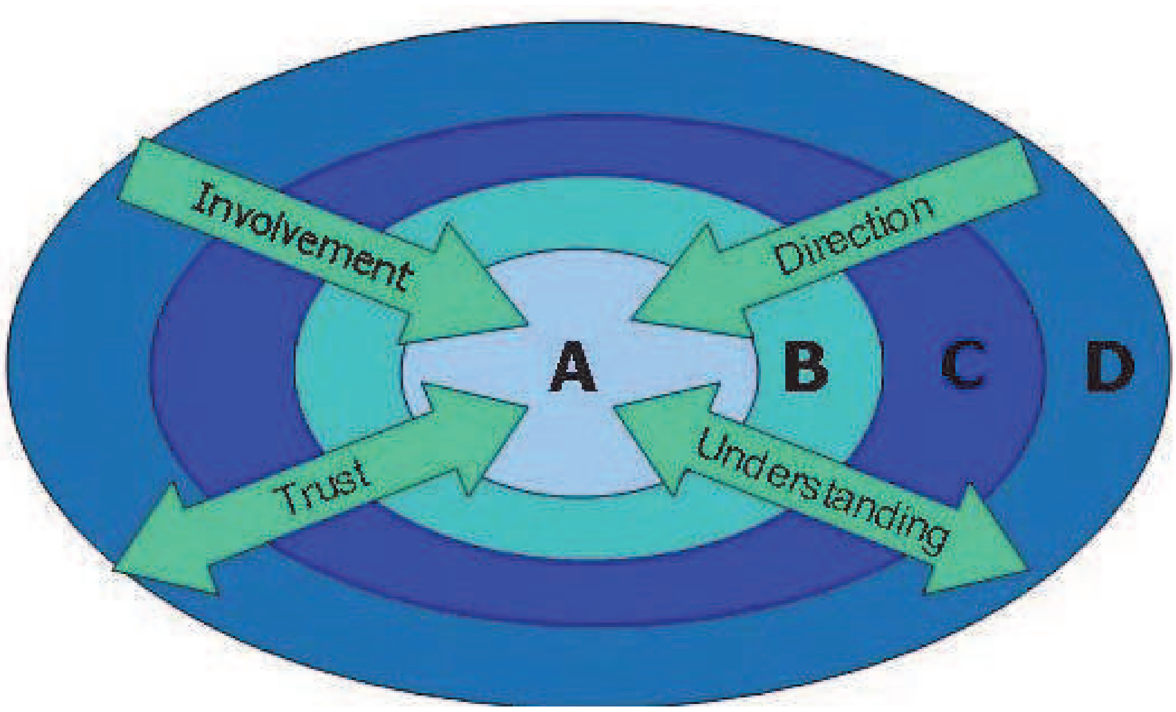


Fig. 1. The concept of the Circles of Influence (from Cardwell et al., 2009).

Currently, Shared Vision Planning is being applied in Peru, in the setting of a nation-wide water reform, prompted by the adoption of a new law in March of 2009. This law promotes the implementation of Integrated Water Resources Management (IWRM) at the basin scale through stakeholder participation, multi-sectoral integration and decentralization of planning and management to the basin level. In order to build institutional capacity for the development of IWRM plans in Peru, the World Bank and The Inter-American Development Bank are funding a pilot project – the Water Resources Management Modernization Project of Peru (PMGRH) – targeting capacity building in six pilot basins. The pilot basins are located in the Pacific coast, ridden with water management problems due to increasing economic development, population growth, and very limited water resources. In collaboration with the National Water Authority of Peru, the International Center for Integrated Water Resources Management (ICIWaRM), a Category II UNESCO Center in the US, is supporting the project through technical advice and conducting training workshops with water managers and stakeholders about participatory planning processes based on Shared Vision Planning principles.
Table 1 summarizes the seven steps of Shared Vision Planning and compares the process with the proposed frameworks of Liu et al. (2008) and Mahmoud et al. (2009) to show the similarities despite the different perspectives from academics and practitioners.

<table>
<tr><th>Integrated Modeling Approach
Liu et al. (2008)</th><th>Scenario Analysis
Mahmoud et a.l (2009)</th><th>Shared Vision Planning
Werrick and Whipple (1994)</th></tr>
<tr><td>--</td><td>--</td><td>(1) Build a team: identify circles of influence: planners, stakeholder representatives, agency leads, advocacy groups & decision-makers.
Identify Problems and Opportunities</td></tr>
<tr><td>(1) Identify and formulate the important focus questions, using science and stakeholder input</td><td>--</td><td>(2) Develop Objectives and Metrics for Evaluation</td></tr>
<tr><td rowspan="2">(2) Define scenarios based on focus questions and based on key external forcings, important and highly uncertain</td><td rowspan="2">Scenario Definition</td><td>(3) Describe current status quo: what happens if we do nothing?</td></tr>
<tr><td>(4) Formulate Alternatives to the status quo, through broad participation</td></tr>
<tr><td>(3) Develop conceptual basis for numerical models to be built and generate data for scenarios</td><td>Scenario Construction</td><td rowspan="4">(5) Evaluate alternatives and develop study team recommendations (Compare alternatives against the status quo, and evaluate them with the metrics and indicators previously developed.)</td></tr>
<tr><td>(4) Develop modeling system, calibration and validation. Adjust conceptual model</td><td></td></tr>
<tr><td>(5) Construct scenarios by deriving model inputs and collecting outputs from model runs</td><td>Scenario Analysis</td></tr>
<tr><td>(6) Perform indicator analysis on scenario outputs: sensitivity analysis to understand main controls and uncertainty sources. Compare scenarios</td><td>Scenario Assessment</td></tr>
<tr><td>--</td><td>--</td><td>(6) Institutionalize Plan (ensure recommendations will be acted upon, requires written agreement to act according to the findings regardless of political and administrative leaderships)</td></tr>
<tr><td>(7)Informed Decision-making</td><td>Risk Management</td><td rowspan="3">(7) Implement and update the Plan (~adaptive management</td></tr>
<tr><td>(8) Monitoring & post-audit</td><td>Monitoring</td></tr>
<tr><td>(1) Repeat, new cycle</td><td>Repeat</td></tr>
</table>

Table 1. Comparison of the approaches from Liu et al. (2008), Mahmoud et al. (2009) and Werrick and Whipple (1994).

5. An evolving system: Uncertainty, DSS and adaptive management

Living in a changing world, it is evident that even if planning and management are implemented as particular actions, they are an ongoing process over the long-term. Consequently, Integrated Water Resources Management is portrayed as a spiral where the implementation of past plans is monitored and the process is re-evaluated and re-directed based upon our most current, new information. In other words, we have to plan for an uncertain future, then deal with it when it becomes the present, and learn from it when it becomes the past. Such an acknowledgement is the basis of adaptive management.

Everyone knows the future is uncertain, but how do Decision Support System Models deal with uncertainty? To what extent and how is uncertainty incorporated into DSS and how is it communicated? The truth is that uncertainty is a difficult concept to work with and is often not well represented in models and decision support tools. Many systems dynamics models state as a disclaimer that the specific values provided by the model are to be interpreted as a relative measure in comparison to other alternatives, but never as absolute numbers. This is well accepted because it still allows the comparison of different management alternatives and an overall view of their impacts in the entire system. While uncertainty can be accounted for in specific model components (physical land surface and hydrologic models) once the intention to do so is there, it may be harder to represent it accurately in systems dynamics models, perhaps due to the inability to accurately represent and blend uncertainties from many different model components of the system (i.e. behavioral and socio-economic components).

There are many sources of uncertainty in simulations: uncertainty contained in the input data (climate change projections), in the model structure formulation (recharge, runoff and evaporation transformations), and arising from issues related to boundaries and scales (e.g., regionalizing soil parameters).

Uncertainty inherent to structural representations of the physical world reflects the lack of proper understanding of physical processes or our inability to represent them properly, much less crossing boundaries of scale. As an example, in basins in Arizona that constitute some of the most instrumented and studied watersheds in the world, the quantification and the spatio-temporal characterization of natural recharge into the regional aquifer remains a formidable challenge. The estimates currently used in hydrologic models are based on empirical relationships aggregated at the basin scale that were developed 20 years ago (Anderson, 1992).

When developing a DSS model, different sources of uncertainty can be represented in different ways. During a collaborative process, stakeholders and decision-makers can decide on what sources and measures of uncertainty need to be explicitly represented in the model and which ones may better be addressed through other means. For example, climate change projections are very uncertain but a multi-model envelope of uncertainty can easily be represented using the wettest and driest models (or hottest and coldest) as the extreme cases, and assuming that future rainfall (or temperature) will fall somewhere in between these extreme cases. All the projections of climate models falling within the wettest and driest models can be averaged, providing what can be used as the highest-likelihood possibility (Hagedorn et al. 2005). Such envelopes of uncertainty in inputs that drive land-surface and hydrologic models can easily be propagated or transmitted from the input variables to the output variables (Serrat-Capdevila et al. 2007). On the other hand, there are uncertainties regarding issues that are difficult to quantify but still have important impacts on decision-making, such as changes in economic drivers, land use cover, institutions and policies. These uncertainties may be better handled through scenario development, where alternative futures – independent of our decision-making process – can be accounted for. On the other hand, information gaps identified during model development can help identify areas of uncertainty and consequently direct research and monitoring activities.

In some cases, uncertainty can be constrained and minimized to a certain extent with studies and research, but it will always be there, especially when trying to assess the future. Acknowledging uncertainty, the concept and practice of **adaptive management** presents a framework for natural resource management under uncertainty that aims at reducing uncertainty through observation during and after management interventions. In other words, adaptive management is a decision-making process that attempts to manage systems in order to maximize both the short-term benefits of management; and the gaining of new understanding to improve management over the longer term. To accomplish the second goal – learning about the system – adaptive management relies on a few basic steps:

a. Characterizing the sources of uncertainty in the system. What are the poorly understood processes in our system and where does the uncertainty arise from?
b. System observation and monitoring of system response to management actions, during their implementation and afterwards. Is the system responding to management interventions as it was expected?
c. If the system is not responding as was expected, different potential explanations can be developed and tested in future management implementations. Such explanations of why the system behaved as it did can either be consistent with our previous understanding of the system, but can also question it. Information and data gathered in future management interventions could be used to validate or invalidate such explanations. This is also known as testing assumptions and hypothesis.
d. Including and assimilating new data and information in a conceptual and numerical representation of the system, embodying the current understanding of how it functions.
e. Management can be specifically geared towards tackling domains of the system where less is known about its functioning or where major uncertainties lie. This can conflict with management goals to maximize beneficial use of the resource in the short term, but is considered a benefit for the long-term as it is likely to reduce uncertainties on the system.

Flexibility is an important aspect of a good adaptive management practice. Institutions should be able to change past policies based on the observed impacts such policies had on the system. The key to this essential feedback linking the latest observations with the next decision-making steps is that it requires close collaboration between those who monitor, study and interpret the behavior of the system with those who do the decision-making. Traditionally, these groups of people belong to different institutions, the communication among which is not necessarily fluid. It is for this reason that a true adaptive management mechanism must also foster new organisms and institutional strategies that will be able to put new knowledge to use at a practical level. For management to be adaptive, the policies must be flexible, not just the institutions.

As real-world systems are often very complex, adaptive management must make use of modeling tools to properly simulate and understand how the system functions. Ideally, as previously mentioned, this forces decision-makers, scientists and model developers to work collaboratively in a cycle of management decisions, implementation, monitoring, interpretation of new data, and inclusion in conceptual and numerical models of the system to help validate past interpretations and/or provide new working hypothesis of how the system behaves.

To the present date, DSS models have mostly been viewed as a product that can be developed to help answer management and planning questions at a given time. It is only very recently that DSS models are starting to be perceived as evolving tools. Rather than developing and using them once, they offer greater benefits when they are dynamically changed over time to represent the evolving present, becoming a working tool that may never be a *finished product* but a product to work along the years. In participatory planning processes this allows the model to be a common representation of the system and the DSS model and supporting documentation can be like an "accountability trail" of what has been done in the past. In adaptive management practice, a DSS model will have to be updated as ongoing policies and management actions are implemented. Model updates will reflect modifications in the *engineered system layer* (canals, pipes, wells, dams, water re-allocations, changes in use efficiencies, changes in land use cover, etc.) as well as new or modified understanding gained through adaptive management on how the system works.

The issues of model updates and institutional flexibility can be well illustrated by the worries of many stakeholders in the San Pedro Basin, collected in a study to evaluate the contributions of the collaborative process in the basin. Being able to feed current, accurate and updated data into the model was a concern for the future that relates well with institutional limitations. A modeling team from the University of Arizona had ensured model and data accuracy, along with technical people from different government and state agencies involved in the process. The point was raised that if the modeling team left the collaboration, no human capabilities existed within the basins' managing institutions to easily take over and continue the modeling work. Local capacity building to update and modify the model was necessary: *Otherwise, if [the main modeler] leaves the State and stops working on it, nobody is able now to take care of things and move on from here.* A comment by one top level policy person illustrates the precarious institutional integration and the need for new flexible institutional arrangements: "*The model will help us a lot in our planning and zoning, our municipalities and county entities, water districts, water planning, etc. [...] my concern is how to keep it up to date with future science, options, and alternatives. If federal funding fails to help [the process] …if no more money comes, all will be lost.*" (Serrat-Capdevila et al., 2008).

The final important point to make here is that an integrative modeling approach in adaptive management institutions will be essential in these types of contexts for many reasons. Decision makers usually use (or benefit from the use of) medium or coarse resolution models in system dynamics platforms (DSS models) that incorporate findings of more refined models in a simplified but still accurate manner. As new information and understanding becomes available, these DSS models are likely to be unsuited to the assimilation of such information. Instead, the more detailed physical models that support and inform system dynamics simulations, are more likely to accommodate new data properly and help improve the understanding of that particular component of the system. Once this is accomplished, the DSS model can be modified accordingly to accurately represent new findings in a simplified way. The full potential of adaptive management can only be reached when it is coupled with an integrative decision support systems modeling approach and with continued research and observation.

6. Conclusion

Decision Support Systems have transitioned from engineering tools to systems that provide frameworks for stakeholder participation to guide, inform and support decision making in a transparent and more sustainable way. The research and past experiences presented in this chapter have shown that participatory planning and management processes can greatly benefit from an integrative and holistic modeling approach. Models of different resolution and complexity that serve different purposes can be used to inform each other through feedbacks. While high-resolution Land Surface Models are necessary when there is a need to accommodate in detail the processes in the physical environment (such as the land-atmosphere partitioning of water and energy, the role of vegetation and the interactions between surface and groundwater hydrology), medium- and coarse-resolution models are typically better suited to modeling human interventions on the environment (such as land-use management, engineering infrastructure). Medium resolution models allow us to represent water allocation and re-distribution within the system and across uses, while coarse resolution models are used to properly describe socio-economic and institutional aspects of water management over the natural and engineered system, with a resolution at the scale of the sub-watershed. In addition to providing an efficient way to represent the coupled natural-human system, a major benefit of multiple resolution modeling is that information and findings can be readily transferred across models and used for model refinement. Information regarding natural processes, climate change impacts and feedbacks in the natural system can be up-scaled to higher level models, while behavioral and policy feedbacks from the socio-economic and institutional models can be used to drive lower resolution models and assess impacts on the natural system.

This integrated modeling approach can be the scientific foundation for participatory planning processes and the collaborative development of decision support tools. The combination of structured stakeholder participation and the use of integrative modeling will allow the proper identification of problems and management objectives in the basin, as well as a better shared understanding of the system functioning, and the development of future scenarios and management alternatives. Based on conflict resolution concepts, this methodology will not only lead to agreed-upon management solutions, but also to a well informed and educated stakeholder community in the basin. Sustainable learning comes with a better understanding of the system as a whole; and problem-solving, over the long term, can benefit from the human capital among individuals involved in participatory processes and the groups they represent. Past studies have pointed out the importance of human capital in society over economic welfare, as well as the mechanisms for ensuring it (education, research, health care, social investments), as the key quality required to address environmental and sustainability challenges. The reinvestment of resources towards human capital (knowledge) in a higher priority over economic capital can be in itself a definition of a sustainable system.

This resonates well with the learning goal of adaptive management. In the present time of rapid economic and environmental change, the future now seems to be more uncertain than ever. With the influence of climate change, the premise of a stationary state on which much of water resources planning and management are based, is now compromised. It is likely that we will have to change the ways in which we extract and use information from the past to predict the future. The implementation of efficient adaptive management mechanisms combined with integrative multi-resolution modeling capabilities will have to balance the search for new understanding and the short-term economic benefits of management.

Currently, the main challenge to achieving efficient adaptive management remains to provide within existing institutional arrangements, sufficient flexibility and the capacity to close the feedback loop between system monitoring, modeling and scientific analysis, stakeholder participation and iterative decision-making. As this is accomplished, it will enable water resources management to shine through the lenses of economic efficiency, social equity and environmental sustainability.

7. References

Anderson, T.W., Freethey, Geoffrey W. & Tucci, P. (1992). Geohydrology and Water Resources of Alluvial Basins in South Central Arizona and Parts of Adjacent States, U.S. Geological Survey Professional Paper 1406-B, United States Government Printing Office, Washington.

Cardwell, H, Langsdale, S. & Stephenson, K. (2009) The Shared Vision Planning Primer: How to incorporate computer aided dispute resolution in water resources planning. Available online at:
http://www.sharedvisionplanning.us/resReference.cfm

Chambers, R. (1994). "Participatory rural appraisal (PRA): Challenges, potentials and paradigm" World Development, Elsevier, vol. 22(10), pages 1437-1454, October.

Forrester, J.W. (1968) *Principles of Systems*, 2nd ed. Pegasus Communications.

Gupta HV, Brookshire, DS., Tidwell, V. & Boyle, D. (2011 in press), *Modeling: A Basis for Linking Policy to Adaptive Water Management*, Chapter 2 in Brookshire D, HV Gupta, and P. Matthews (Editors), *Water Policy in New Mexico: Addressing the Challenge of an Uncertain Future*, RFF Press, Resources for the Future Book Series: Issues in Water Resources Policy Series.

Hagedorn, R., Doblas-Reyes, F.J. & Palmer, T.N., (2005). The rationale behind the success of multi-model ensembles in seasonal forecasting – I. Basic concept. Tellus 57A, 219–233.

Kang, D.S. & Lansey, K. (2011) Development of a Water Management DSS for the Upper San Pedro River Basin (To be submitted to journal).

Liu, Y., Gupta, H., Springer, E. & Wagener, T., 2008. Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. Environmental Modelling & Software 23 (7), 846-858.

Loucks, D.P. & da Costa, J.R. (1991) Decision Support Systems, Water Resources Planning, NATO ASI Series G: Ecological Sciences, Vol. 26. ISBN 3-540-53097-5 Springer-Verlag.

Loucks, D.P., Stedinger, J.R. & Haith, D.A. (1981) Water Resource Systems Planning and Analysis, ISBN 0-13-945923-5 Prentice-Hall, Inc.

Maass, A., Hufschmidt, M.M., Dorfman, R., Thomas, H.A., Marglin, S.A. & Maskew Fair, G. (1962) Design of Water-Resource Systems, New Techniques for Relating Economic Objectives, Engineering Analysis, and Government Planning. Harvard University Press, Cambridge Massachusetts.

Mahmoud, M., Liu, Y., Hartmann,H., Stewart,S., Wagener, T., Semmens,D., Stewart, R., Gupta, H., Dominguez, D. & Dominguez, F. (2009) A formal framework for scenario development in support of environmental decision-making. Environmental Modelling & Software 24 (7), 798-808.

Meadows, D.H., Meadows, D.L., Randers, J. & Behrens III, W.W., (1972) The Limits to Growth. New York: Universe Books. ISBN 0-87663-165-0

O'Brien, K.L. & Leichenko, R.M., (2000). Double exposure: assessing the impacts of climate change within the context of economic globalization. Global Environmental Change 10 (3), 221-232.

Passell, H.D., Tidwell, V., Conrad, S.H., Thomas, R.P. & Roach, D. (2003) Cooperative Water Resources Modeling in the Middle Rio Grande Basin, Sandia National Laboratories Internal Report, SAND2003-3653.

Richter, H. E. (2006). Participatory learning on the San Pedro: designing the crystal ball together. Southwest Hydrology 5(4): 24–25

Roach, J. & Tidwell, V. (2009) A Compartmental-Spatial System Dynamics Approach to Ground Water Modeling, Ground Water 47 (5), pp. 686-698, doi: 10.1111/j.1745-6584.2009.00580.x

Serrat-Capdevila, A., Browning-Aiken, A., Lansey, K., Finan, T. & Valdés, J.B. (2008) Increasing Socio-Ecological Resilience by placing science at the decision table: The role of the San Pedro Basin Decision Support System Model (Arizona). Ecology and Society 14(1): 37. http://www.ecologyandsociety.org/vol14/iss1/art37/

Serrat-Capdevila, A., J.B. Valdés, J. González Pérez, K. Baird, L. J. Mata & Maddock III, T. (2007) Modeling climate change impacts - and uncertainty - on the hydrology of a riparian system: the San Pedro Basin (Arizona/Sonora), *Journal of Hydrology* 347, 48-66. DOI 10.1016/j.jhydrol.2007.08.028

Tidwell, V. C., H. D. Passell, S. H. Conrad, & Thomas, R. P.. (2004). System dynamics modeling for community-based water planning: application to the Middle Rio Grande. Aquatic Sciences 66:1–16. DOI 10.1007/s00027-004-0722-9.

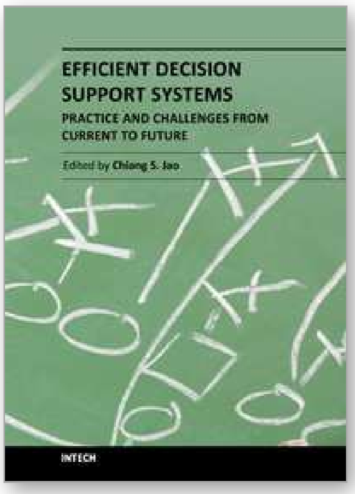
Yalcin Sumer, D. & Lansey, K. (2004) Evaluation of Conservation Measures in the Upper San Pedro Basin. In: *Critical Transitions in Water and Environmental Resources Management*, Pcdgs. World Water and Environmental Resources Congress 2004.

Wagener, T., Liu, Y., Gupta, H.V., Springer, E. & Brookshire, D., (2005). Multi-resolution integrated assessment modeling for water resources management in arid and semi-arid regions. In: Wagener, T., Franks, S., Bøgh, E., Gupta, H.V., Bastidas, L., Nobre, C., de Oliveira, Galvao, C. (Eds.), *Regional Hydrologic Impacts of Climate Change Impact Assessment and Decision Making*, pp. 265e272. IAHS Redbook Publ. No. 295.

Water Resources Council. (1983). Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (Principles and Guidelines).

Werick, W. & Palmer, R.N. When Should Shared Vision Planning Be Used? Institute for Water Resources. Available at: http://www.svp.iwr.usace.army.mil/resReference.cfm.

Werick, W.J. & Whipple, W. Jr. (1994). Managing Water for Drought. National Study of Water Management During Drought. IWR Report 94-NDS-8. U.S. Army Corps of Engineers. Available online at: http://www.iwr.usace.army.mil/docs/iwrreports/94nds8.pdf



Efficient Decision Support Systems - Practice and Challenges From Current to Future
Edited by Prof. Chiang Jao

ISBN 978-953-307-326-2
Hard cover, 542 pages
Publisher InTech
Published online 09, September, 2011
Published in print edition September, 2011

This series is directed to diverse managerial professionals who are leading the transformation of individual domains by using expert information and domain knowledge to drive decision support systems (DSSs). The series offers a broad range of subjects addressed in specific areas such as health care, business management, banking, agriculture, environmental improvement, natural resource and spatial management, aviation administration, and hybrid applications of information technology aimed to interdisciplinary issues. This book series is composed of three volumes: Volume 1 consists of general concepts and methodology of DSSs; Volume 2 consists of applications of DSSs in the biomedical domain; Volume 3 consists of hybrid applications of DSSs in multidisciplinary domains. The book is shaped upon decision support strategies in the new infrastructure that assists the readers in full use of the creative technology to manipulate input data and to transform information into useful decisions for decision makers.