Design Considerations for Watershed Management
Decision Support Systems

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Increasing attention is being paid to the management of water resources on a watershed basis, necessitating a cross-disciplinary approach to data collection and analysis. Traditional assessments of water quality and quantity are being joined by assessments of biology, botany, geomorphology, and anthropological subjects such as economic valuation. This integrated problem domain calls for a reassessment of the information technology tools designed to support the management process. With a comprehensive requirements analysis pulled from a survey of water resource practitioners, the functions necessary for design of a contemporary watershed management decision support system (WMDSS) are outlined and assessed in light of current tools in use today. Following a systems engineering methodology, the WMDSS requirements are analyzed and ranked in order of priority. This yields a ranking for development of tool and information functional groups to support the following assessment types: surface water quality, surface levels and flows, integration, groundwater flows/levels, rainfall/runoff modelling and time series analysis. Functional analysis then provides the architecture and data flows necessary to meet system requirements. The WMDSS functional analysis is concluded with a recommended architecture for design of such a system. This sets the foundation for follow-on work in production and validation of the system.

Key words: watersheds, decision support systems, water quality, watershed modelling, GIS

Introduction

The decisions made by water resource planners and users are frequent and important, and carry wide-ranging consequences. They often result in changes with impacts over decades, and result in significant expenditures of public and private funds. Providing background and planning assistance to inform those decisions is a time-consuming and inexact process. As a result, a significant body of work has focused on the provision of decision support systems (DSS) for water resource planners and users. Today, there is nothing limiting the provision of information technology (IT) based DSS technically; limitations fall rather in the realms of cost and level of production effort.

At the outset of this project, a definition of watershed planning within a management context is necessary. The definition as used by the 1997 Final Report of an Evaluation of Watershed Management in Ontario (PMC 1997) will be used as follows:

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“to provide decision makers with a broad understanding of ecosystem function and status, and to develop recommendations for appropriate resource management in the watershed.”

The key points in this definition are, firstly, that an ecosystem approach is necessary, and, secondly, that the process must provide an understanding to decision makers. Hence, the DSS often consists of several IT tools such as databases, GIS, models and expert systems, etc., to meet these broad requirements.

A shortcoming of past initiatives for the provision of DSS has been to enter the problem definition and solution generation process too far into the loop. A detailed understanding of the needs of system users is therefore missed, resulting in an ad hoc approach to solution generation. Rather than trying to fit solutions to problems, the problems must be thoroughly defined through a requirements analysis. This approach is best suited to a systems analysis methodology, reinforced by the mapping of user needs onto an IT solution architecture. The steps in such a systems analysis are as follows:

1) Define initial problem.
2) Obtain background knowledge.
3) Define final problem.
4) Produce data flow diagram (DFD).
5) Produce program code (object-oriented analysis/design).
6) Validate DSS with real-world problem.

This paper reports on the first four phases of the systems analysis.

**Initial Problem Definition**

To orient the problem within the systems analysis process, Fig. 1 has been produced, detailing the problem space faced by watershed managers and demonstrating the position played by a management system and available modelling tools within that system.

**Process Inputs to Water Resource Management**

Taking the general model above, non-physical inputs and boundary conditions plus physical inputs and boundary conditions constitute the process inputs, i.e., the regulatory, financial, temporal, practical and physical environment in which water resource decisions are made.

**Requirements Analysis**

In order to conduct a requirements analysis, it is important to first define some key terminology (PMC 1997). The hydrogeographic context in which water resource decisions are made is the watershed, defined as the entire catchment area, both land and water, drained by a watercourse...
and its tributaries. A subwatershed is the catchment area drained by individual tributaries to main watercourses. The PMC report calls for ecosystem management, following a sustainable use vision. Watershed management then becomes the process of managing human activities in an area defined by watershed boundaries in order to protect and rehabilitate land and water, and associated aquatic and terrestrial resources, while recognizing the benefits to orderly growth and development. It is a process which involves Conservation Authorities (CA), municipalities, developer landowners (at the request of approving agencies), provincial agencies in fulfilling their mandates to protect and preserve the environment, federal programs for designation of heritage areas, and community-driven initiatives. The drivers behind watershed projects include environmental resources, land use changes, land use management, and redevelopment/restoration efforts such as habitat restoration, pollution abatement and environmental enhancement options.

As a first step in capturing the broad requirements which apply to a DSS for water resource users and planners, the key stakeholders and their needs bear the following examination.

**Government agencies**

Government agencies include local (CA and municipalities), provincial and federal agencies. They (i) prepare realistic and achievable long-term resource management plans; (ii) protect, enhance and restore fish and other aquatic resources; (iii) protect water quality; (iv) protect water quantity; (v) develop private and municipal water and sewage services;
(vi) identify future development opportunities; (vii) conduct land management activities; (viii) identify and protect wetlands; (ix) work in cooperation with the land use planning system; and (x) reduce the cost of remediation.

Affected parties

Affected parties include individuals or groups whose lifestyles or business or land use occupancy practices may be positively or negatively impacted by watershed management decisions. They (i) represent views of landowners and the agricultural community; (ii) protect resources from land use changes; (iii) improve water quality and quantity; (iv) prevent environmental degradation; (v) address private landowner rights; (vi) streamline the approvals process; and (vii) reduce barriers to development and protection in watersheds.

Special interest groups

Special interest groups include "friends of" groups, e.g., U.S. National Watershed Network (Keppy 1997) and NGOs. They protect recreational green space and establish criteria for development and land use changes.

Community members

Community members are residents of the watershed. They restore water quality and ecosystem integrity.

The above needs now must be reworked into a logical categorization. Options are to group by organization or by subject. The latter will be adopted initially, resulting in the following broad requirements: (i) assist in the assessment of water quantity (e.g., using an approach as shown in Fig. 2) and water quality; (ii) support remediation planning aimed for in-stream and riparian zone; (iii) support protection planning of water quality, water quantity and ecosystems; (iv) support pollution prevention planning; and (v) support watershed management administration efforts by providing planning guidance documentation and information, a mechanism to resolve interjurisdictional disputes, and assisting in minimizing capital outlays through optimization.

The cornerstone of Phase 1 was to carry out a comprehensive requirements capturing from water resource management groups, both from an engineering consulting perspective and a government agency perspective. To this end, 50 user surveys were mailed to target groups in mid-October 1998. Target groups consisted of engineering consulting firms (33), provincial/regional/municipal government bodies (9), and Conservation Authorities (8) all from Eastern Ontario. Respondents ranked their preferences for tool and information functionality within a WMDSS, as follows, in order of priority:

1) Surface water quality assessment.
2) Surface flows and elevations assessment.
3) Integration of watershed themes.
4) Groundwater flows/levels assessment.
5) Rainfall/runoff modelling.
6) Time series analysis.

This list serves as the priorities for production of functionality in the subsequent system development.

A proper requirements analysis necessitates taking these broad requirements and breaking them down into their subrequirements, such that a functionality mapping can be done.

**Background Knowledge**

The tools which are available to water resource planners, and the means by which they may be integrated into a DSS, are two areas requiring investigation. A number of schemes have been used to organize and describe modelling tools. The definitions used herein will be as per the descriptions by James (1993). The general approach to modelling involves two broad stages: analysis of the system and synthesis of a mathematical replica of the system (James 1993). The steps taken in the formulation of a model are shown in Fig. 3. Critical in commencing the modelling process is the establishment of clear objectives against which the model can be measured to determine success. Next, the theoretical background govern-
The physical system must be reviewed and updated with the latest information. Then the actual model can be formulated, beginning with a decision about the type of model which best meshes the objectives to the physical problem space.

The model structure is created next, generally using a top-down approach with major model subdivisions being defined and further broken down into constituent elements. These elements will need to be represented by (an) equation(s). The necessary input data and information flow can be mapped to the structure. Solution techniques must be selected; while exact analytical solutions are preferred, the complex nature of most mathematical models describing water quality will require numerical solution techniques. Final steps involve the production of the actual computer program with the critical calibration, validation and sensitivity analysis processes following. The expansion in use of IT to provide modelling support has resulted in multiple approaches to system design and model types. Figure 4 illustrates this in the context of environmental decision making, and Fig. 5 offers further insights into how models used in the analysis of water quality (as an example) are classified.

While each modelling problem will pose individual problems, a common source of difficulty lies in establishing the key governing equations that characterize the problem. Over simplification can lead to a poor, inexact result, while too much complexity can lead to increased costs and time consumption and a reduction of flexibility.

In this analysis, models also need to be differentiated according to what aspect of the watershed they model, be it surface flows, ground water flows, chemical constituents, biological processes, etc. The last introductory concept to cover is to place decision support within the context of IT support to environmental problem solving. Looking at Fig. 4, it can be seen that decision support joins dynamic modelling, expert systems and artificial neural networks as the approaches to problem solving.
Fig. 4. Information technology system design (after Lein 1997).

Fig. 5. Classification scheme for water quality model types (after James 1993).
in this domain. The following individual and complementary approaches are defined (Lein 1997).

1) *Decision support.* An IT that recognizes the capabilities of a computer to support decision makers through such functions as access to data and models for problem formulation and alternative evaluation.

2) *Dynamic modelling.* An IT model representing a system in an unsteady state, such that inputs and coefficients may vary with time, giving rise to a time-varying output.

3) *Expert systems.* An IT with the capacity to perform reasoning operations using human expert knowledge-based rules.

4) *Artificial neural networks.* An IT that simulates the functionality of the human brain in decision making.

Decision support borrows heavily from systems theory in its representations of and solving methodologies for problems, hence the approach taken in this project.

**Physical Models**

Having placed decision support systems within the broader context of IT tools, the next step down is to examine some of the physical models that a decision support system can draw upon in its tool set to help support decision makers. Models need to be assessed based on such criteria as the subject of the model, its data requirements, its availability (cost), its user friendliness and its ability to be integrated into a DSS. Application-focused models can be broken down by subject area, as discussed earlier, and can be categorized as either digital process models, spreadsheet systems, or general purpose simulation programs (Lein 1997), not forgetting of course analytical models on which many of the digital models are based. The bulk of physical models familiar to environmental practitioners fall into the first category of digital process models, those being models developed to simulate key environmental processes. Table 1 summarizes a number of digital process models for water quality, surface flows, rainfall/runoff, subsurface hydrology, and sediment transport, and online databases and watershed management programs.

It is also worth mentioning the use of 1-D codes or spreadsheet models for particular physical problems encountered within watersheds. It is necessary to weigh the additional cost of a digital process model in terms of the time and expertise required to use it against the increase in precision of the results it provides. In many instances it may well be sufficient to employ a simple 1-D code or a spreadsheet to produce a "90%" solution to a problem, rather than investing the resources necessary to produce a "95%" solution. A good example of this is in the case of making rapid time-of-travel estimates for emergency contaminant spills — rapid estimates gained through use of empirical estimates offer the best approach (Jobson 1997). 1-D codes or spreadsheet solutions are available...
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<td>QUAL2E (Sep 95)</td>
<td>PC-WIN DNS</td>
<td>U.S. EPA Watershed Modeling Section, 401 M Street, S.W., Washington, DC 20460</td>
<td>Simulates the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the dissolved oxygen balance.</td>
<td>Free: download at <a href="http://www.epa.gov">http://www.epa.gov</a></td>
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<td>AGNPS 98</td>
<td>PC-WIN DPM</td>
<td>ARS National Sedimentation Laboratory, Oxford, Mississippi</td>
<td>Simulates sediment and nutrient transport from agricultural watersheds. The basic components of the model are hydrology, erosion, sediment transport, nutrient transport, and chemical oxygen demand.</td>
<td>Free: download at <a href="http://www.sedlab.olemis.edu/AGNPS98.html">http://www.sedlab.olemis.edu/AGNPS98.html</a></td>
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<td>CORMIX 3.2 Dec 96</td>
<td>PC-DOS DPM</td>
<td>U.S. EPA-CEAM College Stn Road, Athens, GA 30605-2700</td>
<td>Analysis, prediction and design of aqueous toxic conventional pollutant discharge into diverse water bodies.</td>
<td>Available at no charge via CEAM disk exchange or download at <a href="http://ftp.epa.gov/epa/ceam/wwwhtml">http://ftp.epa.gov/epa/ceam/wwwhtml</a></td>
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<td>SWAT 98.1</td>
<td>PC-WIN95</td>
<td>Grassland, Soil and Water Research Laboratory, Temple, TX</td>
<td>SWAT is a continuous time model (daily time step) that is required to look at long-term impacts of management (i.e., reservoir sedimentation over 50–100 years) and also timing of agricultural practices within a year (i.e., crop rotations, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing).</td>
<td>Free – download at <a href="http://www.brc.tamus.edu/swat/swat/swatdoc.html">http://www.brc.tamus.edu/swat/swat/swatdoc.html</a></td>
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<td>WASP5 93</td>
<td>PC-DOS DPM</td>
<td>U.S. EPA</td>
<td>Contaminant fate and transport model in 1-D, 2-D, 3-D.</td>
<td>Available at no charge via CEAM disk exchange or download at <a href="http://ftp.epa.gov/epa-ceam/wwwhtml">http://ftp.epa.gov/epa-ceam/wwwhtml</a></td>
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<td>HSCTM2D</td>
<td>PC-DOS DPM</td>
<td>CEAM</td>
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<td>2-D vertically integrated surface water flow, sediment transport and contaminant transport modelling suite.</td>
<td>Available at no charge via CEAM disk exchange or download at <a href="http://ftp.epa.gov/epa_ceam/wwwhtml">http://ftp.epa.gov/epa_ceam/wwwhtml</a></td>
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<td>SWMM</td>
<td>PC-DOS DPM. Also in EX version for Expert System</td>
<td>U.S. EPA CEAM</td>
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<td>SWMM is a large, complex model capable of stimulating the movement of precipitation and pollutants from the ground surface through pipe and channel networks, storage treatment units and finally to receiving waters. Both single-event and continuous simulation may be performed on catchments having storm sewers and natural drainage for prediction of flows, stages and pollutant concentrations.</td>
<td>Available at no charge via CEAM disk exchange or download at <a href="http://ftp.epa.gov/epa_ceam/wwwhtml">http://ftp.epa.gov/epa_ceam/wwwhtml</a></td>
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<td>SMADA</td>
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<td>Complete hydrology package included as a number of separate executable files. These programs work together to allow hydrograph generation, pond routing, storm sewer design, statistical distribution and regression analysis, pollutant loading modeling, matrix calculation, and others.</td>
<td>Free: download at&lt;br&gt;<a href="http://www.cee.engr.ucf.edu/">http://www.cee.engr.ucf.edu/</a></td>
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<td>MIDUSS</td>
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<td>DPM</td>
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<td>Stormwater runoff program for the design and collection of a network of storm sewers and channels.</td>
<td>Alan A. Smith&lt;br&gt;$595 US</td>
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<td>Subsurface hydrology</td>
<td>MOD-FLOW 96</td>
<td>Modular 3-D finite-difference ground water flow model</td>
<td>U.S. Geological Survey Hydrologic Analysis Software Support Program, 437 National Center Preston, VA 20192</td>
<td>This code is a block-centred finite difference code that can simulate a range of aquifer types. MFI—data input program for MODFLOW, MODPATH, and MOC3D. MODPATH—a particle-tracking post-processor model for MODFLOW (Unix only). ZONEBUDGET—program for computing subregional water budgets for MODFLOW ground-water flow models.</td>
<td><a href="http://water.usgs.gov/software/modflow-96.html">http://water.usgs.gov/software/modflow-96.html</a> e-mail: <a href="mailto:h2osoft@usgs.gov">h2osoft@usgs.gov</a></td>
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<td>PLASM</td>
<td>2-D finite</td>
<td>difference flow model</td>
<td>Thomas A. Prickett &amp; Assoc., 6 GH Baker Dr., Urbana, IL 61801</td>
<td>The Prickett-Lonnquist aquifer simulation model is a block-centred finite difference code that can simulate 2-D problems in both areal and profile orientation.</td>
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<td>Uses primitive vertically averaged Navier Stokes shallow water equation.</td>
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<td>Online databases</td>
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<td>Dial-up site</td>
<td>U.S. EPA</td>
<td>Repository for water quality and environmental monitoring data; chemical, physical and biological data pertaining to quality of U.S. waterways.</td>
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<td>BASINS 2.0</td>
<td>ArcVIEW script program</td>
<td>U.S. EPA</td>
<td>BASINS version 2.0 is a customized ArcView GIS application that integrates</td>
<td>Public domain</td>
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<td>environmental data, analysis tools and modeling systems.</td>
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<td>RAISON</td>
<td>Regional analysis by intelligent</td>
<td>National Water</td>
<td>A data analysis tool that provides an intuitive environment for displaying data</td>
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<td>systems ON microcomputers</td>
<td>Research Institute, Environment Canada, 867 Lakeshore Road, Burlington, ON L7R 4A6</td>
<td>and analyses in the context of the local geography.</td>
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Notes: DPM = Digital process mode. DNS = Deterministic numerical simulation. General approach: find common, validated, inexpensive modelling tools running on a PC.
for all conceivable physical watershed problems, such as ground water
flow (Anderson and Woessner 1992), oxygen sag, river flow with disper-
sion and moving segments, discharge to a river, lake thermal structure,
lake hydrodynamics, lake chemistry, and lake biology (James 1993).

Other Models

There is a multitude of other elements that combine to form the
watershed of concern to managers, aside from the physical characteristics
mentioned previously. The following elements are included (after Lein
1997).

1) Botanic. Elements such as species diversity/species of interest/
trends and structure.
2) Geologic. Elements such as lithology and structure.
3) Human. Elements such as inhabitance (subset of land use)/trends
   in populations, culture, economy/economic value of watershed
   elements, and land use/land use trends.
4) Climatic. Elements such as weather elements, patterns, and pre-
   cipitation levels/seasonal variations/trends.
5) Zoologic. Elements such as species diversity/species of interest/
trends, food webs and patterns.

A plethora of models exist for many of the above listed elements.
They find infrequent use in generalized watershed management systems,
being overly specific to be of use. Specialized problems do make use of
some specialized models — recent efforts to examine the sensitivity of
basins to climate change, for example, have made good use of the
GOLEM model (Tucker and Slingerland 1997). The above elements do
however find expression through grouped or ecosystem-based measures.
One method of accomplishing this is through use of indices. The trend
towards development of integrated systems will give increasing weight
on methods of successfully incorporating a large range of elements into a
management system; this is both the bane and the challenge of contem-
porary watershed decision support system designers.

Indices and GIS

The concept of trophic states for water bodies has been used for
decades. Simply stated, the concentration and loading of nutrients directly
influence the trophic state, such that as levels rise total biomass increases
while species diversity decreases (Droste 1997). Species types and diversity
indices can therefore serve as an indicator of the trophic level. While there
is no question that chemical criteria and toxicological studies serve vital
roles in assessing and controlling water quality, consensus is emerging that
threats to water bodies come not from a single toxicant, but from an array
of stresses, including changes to flows, channel modifications, sedimenta-
tion, excesses in nutrient inputs, etc. (Perry and Vanderklein 1996). This was
clearly demonstrated in Ohio, where the proportion of waters assessed as
degraded by chemical criteria was 50% lower than the proportion assessed when biological assessments were used instead (Karr 1995).

Early bioassessments have today grown into complex indices. The indices in use include the following examples (after Perry and Vanderklein 1996).

1) Saprobic index. A weighted numeric index is used to calculate pollution stress, with organisms in the various saprobic zones (these zones refer to areas of a stream below a pollution source showing particular levels of stress) being assigned an according number. This is multiplied by an abundance value, and the overall weighted average indicated the level of pollution.

2) Percent EPT. This index measures the percent of collected organisms coming from the orders Ephemeroptera, Plecoptera and Trichoptera, these orders all being plentiful in cold high-quality waters and sensitive to pollution.

3) Diversity index. This type of index relies on assessment of the relative abundance of several taxa. Impacted systems show less diversity than unimpacted ones.

4) Biotic index. This type is similar to the diversity index, but relies on a restricted group of organisms, i.e., those found in the benthos.

5) Integrated or multiple index. To overcome the shortcomings of the above indices, integrated measures have been developed such as the popular index of biotic integrity (Karr 1981), which uses the abundance, trophic composition, species composition and condition of fish through a range of ecological levels (individual through community to ecosystem). A similar rapid bioassessment protocol, consisting of eight metrics gathered from two different stream habitats, has been developed by the U.S. EPA.

Indices have seen widespread use in the assessment of river health, and have the potential to be valuable components of a watershed management system. They can be tailored to suit the elements of greatest concern for a particular situation, the only danger in doing so being that customization erodes the comparability of the index to other systems. Some work has sought to overcome site specificity through development of watershed scale indices of biotic integrity that use whole watershed variables for metrics rather than site specific variables, such as the work of Moyle and Randall in California (1998). This work saw development of a watershed-index of biotic integrity (W-IBI) that takes into account native fish assemblages, abundance of native frogs, presence of anadromous fish and the introduction of trout into previously fishless streams.

Another tool which lies outside the sphere of modelling, but inside the sphere of environmental decision support systems, is geographic information systems, or GIS. A GIS offers the most comprehensive and powerful landscape characteristics database available. Landscapes are divided into themes such as soils, geology, vegetation, elevation, etc. In
A GIS acts as a computer-assisted system for the capture, storage, retrieval, analysis and display of spatially referenced data (Arnoff 1991). A GIS by definition then is extremely data hungry, which is often the limiting factor in its application. Widespread attention has recently been paid to the integration of GIS into DSS and other land management efforts. Indeed, such uses figure prominently in the marketing of GIS, many of which come with scripting languages permitting their customization for such uses. Cost can be prohibitive, however, as can be the level of expertise required to use the product. Examples of commercial GIS packages include ArcView, Arc/Info and Grassland. A GIS offers a powerful land use data input function to any watershed management system. Efforts to produce GIS-based DSS have been somewhat successful (Watson and Wadsworth 1996; Montas and Madramootoo 1992; Zhou 1998). A recent example is the Dee Catchment Management Planning Geographic Information System effort in Scotland (Webb and Bacon 1999). This project saw an Arc/Info Unix-based GIS database used as a framework for multi-user efforts to manage the Dee watershed for Atlantic salmon production. While highly successful at meeting this mandate, the system saw limited value as an engine for running the management decision process, due to the lack of accompanying modelling tools. Indeed, because the key parameter channel width was not provided by the GIS data, a separate survey and analysis was required to produce the accessibility index. Access to a modelling toolset is the defining characteristic of a DSS; without that, one is left simply with an aid to data visualization. This is the principle reason why a WMDSS would most likely need development as a stand alone application, with the option for GIS import/export capabilities.

**Decision Support**

The implementation of automated decision support systems has seen widespread application in business management for years. The last decade has seen a spillover into environmental management. Development of DSS hinges on uncovering the decisions which need supporting, and on the process through which the decisions are made. For environmental systems and watershed applications in particular, DSS are often a component of or associated with management tools. Decisions form part of the management process. Management feeds off of information — the applicability of IT support to such a process is clear. The following critical abilities are required for decision-making systems (Lein 1997).

1) Ability to collect information.
2) Ability to formulate models.
3) Ability to govern problems.
4) Ability to analyze problems.
5) Ability to evaluate problems.
6) Ability to implement strategy.

A decision-making system can be viewed as a person vested with the
responsibility to make a decision coupled to a DSS, hence, the DSS must support or assist in some or all of the seven critical abilities listed above. A classification scheme has been developed for decision problems suited to DSS automation, as detailed in Table 2.

It can be seen that many of the problems facing watershed users and planners fit into the types of Table 2. If the task of a DSS is generalized, it can be said that such a system must be designed to support the solution of ill-structured problems: it must furnish its users with a powerful problem-solving environment incorporating models directly into its design. This generalized concept has been broken into functional blocks by Sage (1991), as shown in Fig. 6.

Table 2. Classification of problems suited to DSS automation (after Davis 1988)

<table>
<thead>
<tr>
<th>Problem class</th>
<th>Task definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type O</td>
<td>Mechanistic; non-thought-provoking; compliance with limited alternatives; singular objectives; few complications.</td>
</tr>
<tr>
<td>Type A</td>
<td>Use of computer as visual aid; data sorting and data search; automation of routine computations.</td>
</tr>
<tr>
<td>Type B</td>
<td>Issues related to trade-offs; problems with conflicting objectives.</td>
</tr>
<tr>
<td>Type C</td>
<td>Structural complexity; large in size and scope; difficult to visualize.</td>
</tr>
<tr>
<td>Type D</td>
<td>Complex; dynamic; highly qualitative.</td>
</tr>
</tbody>
</table>

Fig. 6. Critical Components of DSS (after Sage 1991).
For the design of a watershed management DSS, it will also be important to incorporate the functionality associated with the management process: access to key reference information, and support for integrated views of the watershed, will be key. All of this functionality will not come without a price. Development, implementation and maintenance of DSS will require levels of expertise likely not available within many user organizations, such as Conservation Authorities. Such organizations run the risk of not having control of their system unless it is designed with sufficient user friendliness and reference information to reduce or eliminate the need for expert users. Formation of user groups may offer such organizations a way to maintain sufficient levels of control over the design and maintenance of DSS systems.

Integration

The emerging science of integration in watershed management is receiving ever greater attention, as it is realized that integration is essential to the generation of comprehensive management strategies. The Final Report of the WPI Science and Technology Task Group (STTG 1997) in Ontario made significant reference to the critical link of integration in watershed management. The definition for integration given was in realization of the need to understand the interrelationships of the physical, biological and chemical components of the watershed through integration of information across disciplines. This is accomplished through taking a systems view of the watershed (hence the systems engineering methodology adopted for this project) and using an integrative approach to watershed planning with a number of discrete steps: overview the system; define the structure, the affective linkages of the system, and key components to be studied; reduce the system to its constituent components for the purpose of scientific study; study the component parts; reaggregate the system; and re-evaluate the overview focusing on interrelationships and the whole system.

The WMDSS tool must support the above approach, with support for all constituent component parts of the system.

Software Modelling Approaches

There are several software modelling approaches appropriate for design of the WMDSS. The approach chosen must support the system engineering methodology previously outlined and must provide the flexibility to interface with legacy software from the “procedural” days of programming without preventing use of more advanced object-oriented (OO) design paradigms. Once the design approach is chosen, an appropriate language must then be selected.

Conceptualization of a watershed naturally supports an OO approach. Indeed, to the greatest degree the actual watershed with its physical characteristics should be represented in code; program structure then becomes the defining of interrelationships between objects, support-
ing the need for an integrated watershed view completely. Such a pure
OO approach, while conceptually elegant, imposes constraints on formul-
ation of the management side of the software, however. A nod to an
event-based paradigm to fully support inclusion of the “manager-in-the-
loop” is necessary. The explanation of the following paragraphs will make
this point more clear.

One comprehensive OO approach is the Coad, Yourdon and Nicola
object-oriented analysis, design and programming approach (Coad and
Nicola 1993). It contains the following components.

1) Object-oriented analysis (OOA). Works with problem domain classes
and objects.
2) Object-oriented design (OOD). Focuses on human interaction, task
management and data management classes and objects.
3) Object-oriented programming (OOP). Provides implementation
strategies for implementing OOA and OOD results.

The method provides a number of principles in support of the above
components, key among them being methods of organization (object clas-
sification or hierarchy establishment), categorization of behaviour (what
do objects do?) and personification (what are an objects characteristics?).
Objects are defined as instances of their object class (a class is in essence a
template) that performs a defined set of services. Objects act as both
senders and receivers of information to/from other objects.

The method uses an architecture consisting of four major compo-
nents: the human interaction component (HIC), the problem domain com-
ponent (PDC), the task management component (TMC), and the data
management component (DMC). This architecture exhibits marked simi-
larities to the decision support subsystems of a DSS (Fig. 6): HIC=GUI,
DMC=DBMS, TMC=MBMS, PDC=KBMS. In fact, both of these architec-
tures represent logical groupings of functionality that necessarily bridge
between the conceptual framework of the functional allocation phase of
systems engineering and its implementation in software. OOA/D/P is
nothing more than a subset of systems engineering appropriate for use in
defining complex systems.

While the physical domain of the WMDSS (the watershed) can easi-
ly be thought about in terms of a collection of objects of various types, it
is more difficult to include the user and the user’s problem space within
that domain. The user will ask the system to do certain things to or with
the objects defining the watershed being managed. This suggests that a
design philosophy that couples the robustness of the OO approach for the
physical domain to the flexibility of the event approach for the user inter-
action domain is best.

Selection of language can therefore expand from pure OO languages
such as Smalltalk to mainstream tools such as C++, Delphi version 2.0 or
later and Visual Basic version 5.0 or later (the absence of a Web-focused
requirement precludes such languages as Java, which, while offering plat-
form independence, carries a significant speed of operations handicap. All three of these languages offer support for OOA and OOD along with their legacy abilities to code procedural or event-based programs. All also offer integrated development environments (IDEs, more commonly called Visual versions) for form design. Visual Basic version 5.0 was chosen for this project.

A final step in defining the software modelling approach is integration with the systems engineering methodology. This has been accomplished by placing the OOA and OOD phases within the map requirements to functions and synthesize functions steps. Adoption of an OO approach for the physical domain of the WMDSS necessitates production of an object model (in keeping with good systems engineering methodology).

**Government Bodies and Agencies**

An important part of establishing the non-physical inputs to the watershed management problem space involves outlining the responsibilities of the various levels of government. The following paragraphs summarize responsibilities at the federal level -- provincial and municipal responsibilities will vary widely:

**Environment Canada**

*Responsibility.* Leadership on matters of environmental concern, enforcement of federal regulations and national research at centres such as CCIW (NWRI).

*Legislation.* Federal regulations such as the Canada Water Act and the Canadian Environmental Protection Act are shepparded, along with acts specific to international boundaries such as the International River Improvements Act, the Lac Seul Conservation Act and the Lake of the Woods Control Board Act.

**DFO**

*Responsibility.* The Department of Fisheries and Oceans (DFO), on behalf of the Government of Canada, is responsible for policies and programs in support of Canada’s economic, ecological and scientific interests in the oceans and freshwater fish habitat; for the conservation and sustained utilization of Canada’s fisheries resources in marine and inland waters, and for safe, effective and environmentally sound marine services responsive to the needs of Canadians in a global economy.

*Legislation.* Fisheries Act.

**Data Flow Diagram**

A proper requirements analysis necessitates taking the broad requirements and breaking them down into their subrequirements such that a functionality mapping can be done. From the decomposition, the functions needed by the system are identified, ready for incorporation into the level 0 data flow diagram.
The level 0 data flow diagram represents the topmost level of the WMDSS system functional architecture. Each subsystem is further defined through the level 1 model. The following two figures (Fig. 7 and 8) define the complete level 0 DFD and the level 1 DFD for the first portion of the Model Base, as an example.

![Image of DFD Diagram]

**Fig. 7. Level 0 DFD.**

**Conclusion**

The final output of the systems analysis carried out through the phases of this project leads to a system concept that demands an integrated approach to watershed management. Having started the analysis with a comprehensive requirements-capturing process, and having mapped those requirements onto system functions, it is now possible to design a system based on the data flow diagrams produced. The critical features of access to a suite of physical models and the ability to view a complete set of watershed characteristics provide decision makers with all of the necessary information. This analysis has not, however, done anything to alleviate the demand for data; on the contrary, a fully populated WMDSS would require significantly more data than a simpler watershed representation. Further effort is needed in identifying the available data and in developing input interfaces to the WMDSS for that data. To that end, all physical model interfaces are designed as duplex routines such that it is
Fig. 8. Level 1 DFD for Model Base.

possible both to export WMDSS data to the models, and to import existing watershed feature sets from the models. Characterization of the object models in QUAL2E, HEC-RAS, MODFLOW and HEC-HMS, and production of a summation object model for the WMDSS ensures that all pertinent information is covered in such an exchange.

The above analysis offers a firm start point from which a WMDSS may be developed. A similar approach can be taken with different physical models to cater to regionally specific needs (for instance, an urban version would make good use of a stormwater runoff model). In the end, any support for integration in watershed management will pay dividends. This analysis of design considerations should be viewed dynamically. The rapid rate of change in IT may well present options that change the very nature of watershed management. The increasingly ubiquitous Internet may offer a medium through which the public, as the ultimate stakeholder, can participate more fully in the decision making process. Certainly it offers the means of broadcasting the technical results of scenario analysis, permitting a more transparent management process.

References


STTG — Science and Technology Task Group. 1997. The final report of the watershed planning initiative science and technology task group. Ontario MOE publication PIBS 3585E.


