Spreadsheets: flexible tools for integrated management of water resources in river basins

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Abstract In river basins, the boundary conditions to planning and management are highly sensitive to change. Exogenous scenarios, such as the political situation, population growth, employment levels, exchange rates, commodity prices, policy objectives and constraints, are often changing so fast that the analyst must have very flexible tools that can respond to the ever changing circumstances. For adequate planning, time cannot be lost in developing sophisticated tools which may be the perfect solution to the planning problems in theory, but which in practice turn out to be rigid, bound to specific hardware configurations, and in need of specially-trained operators. In this respect, spreadsheets are ideal tools. Spreadsheet tools are flexible, transparent and interactive. They are easy to build, easy to adapt to changing circumstances, easy to debug and very accessible. All over the world people have learned to work with spreadsheets, and although they are not usually acquainted with all the possibilities that such packages have to offer, it is not difficult to train them in spreadsheet modelling. Application of the spreadsheet modelling approach to river basins in Mozambique, Trinidad, Zambia and Ecuador have demonstrated the ease with which individual, case specific components for a decision-support system may be developed.

INTRODUCTION

The time when water resources planning in river basins was almost identical to operations research has long since past. Water resources managers realize that the management of water resources nowadays means, primarily, coping with uncertainty. Our world is developing very fast and the problems we are facing in the allocation of scarce and limited resources grow ever more complex in a rapidly changing society, where policy objectives, interests of stakeholders, economic boundary conditions and political, financial and physical constraints change by the day. Exogenous scenarios, so important for planning, such as the political situation, population growth, employment levels, exchange rates and commodity prices are changing too fast for the analyst to make any reliable long-term forecast of benefits and costs of alternative strategies. Consequently, the attention of decision makers and planners has shifted from the long-term planning, which was so popular in the 1970s, to short-term planning and to strategic decision-making, where the emphasis lies on short-term decisions which least affect the long-term options.
In addition, water resources managers have realized that our water resources are limited and that a water management approach which is orientated towards more allocation of water is in conflict with the sustainable development that we envisage, and that allocation-biased water management merely postpones the imminent problems to be solved by coming generations. Consequently, demand management and the economic pricing of water have become much more important than the mere solution and optimization of an allocation problem.

In today's rapidly changing society, what politicians and decision-makers require most is readily accessible information that allows them to make short-term decisions that do not forego future options. When given the choice, decision-makers would rather have a quick and less accurate answer to a decision problem than a very detailed answer that would take considerable time for research, modelling and analysis. The water resources problems that we are facing today primarily require flexible decision support tools: data bases, systems models and analysis tools with adequate interfaces and communication facilities.

The need for easier interaction with the tools, in particular, has lead to a completely new generation of commercial decision-support tools, including data bases, models and policy analysis instruments, which Abbott et al. (1991) call "fourth generation models". Fourth generation models are available for hydraulic and hydrological computations, and much progress has been made in the development of data bases and policy analysis tools. In the field of water resource systems simulation in river basins, among the most advanced software is IRAS, developed by Resources Planning Associates, Inc. under the guidance of Prof. D. P. Loucks of Cornell University. However, fourth generation tools are not always flexible.

Fourth generation models are expensive in both development and maintenance costs and require major programming efforts. I still vividly recall the observation made by Prof. Loucks at a seminar in Wageningen in 1991, that developing new software requires a disproportionate amount of time for debugging and polishing as compared to the time spent on creativity.

To cope with the ever increasing complexity of the profession, the water resources manager becomes more and more dependent on sophisticated tools and on powerful computers. Technology, computer hardware and software, are advancing so fast that decision-support tools become old-fashioned or inadequate within a matter of years. In addition, the operation of a decision-support tool is often the work of specialists. There have been examples of decision-support tools that were so dependent on the people who developed and operated them, that the tools became useless as soon as the operators left the office.

The danger of this development is that the water resources manager may become so dependent on the software and the people that are familiar with it, that he/she loses track of the processes that are simulated by the system.

Although I am completely convinced of the need for and the value of fourth generation models, I also strongly believe there is a need for tools that allow sophisticated "back of the envelop computations", in the tradition of the slide rule and the programmable pocket calculator, but much more powerful. For this purpose, spreadsheets are excellent tools. By now there are few people, particularly in the new generation of professionals, who are not conversant with spreadsheets. Already a considerable set of spreadsheet modules has been developed, which can be used as a sort of toolbox by any
professional with knowledge of spreadsheets, for the analysis of alternative water resources development strategies in complicated river basin systems.

In the following, I shall present a brief outline of the track record of spreadsheet modelling for water resources, both with regard to their functionality and their limitations.

SPREADSHEET MODELLING — EXPERIENCES, ADVANTAGES AND DISADVANTAGES

During the last ten years, considerable developments have taken place in the use of spreadsheets for water resources planning. Perhaps the first serious application of spreadsheets in water resources modelling was that of Olsthoorn (1984), who wrote an article in the Dutch journal for water engineering, H₂O, showing how simple it was to make a groundwater model in a spreadsheet. The article, to me, was an eye-opener. How could such a simple tool as a spreadsheet solve complicated engineering problems?

Many people, maybe independently, followed the example. Table 1 gives an example of a wide range of spreadsheet models, which is probably not a conclusive list. One can see that spreadsheet models already cover many aspects of water resources modelling and planning.

Why are spreadsheet models so popular?

Spreadsheets have quite a number of advantages over source code written programs. The most important one is their accessability. All over the world, all kinds of professionals have become acquainted with spreadsheets, much in the same way as professionals have started to use word processing. Spreadsheets are accessible, transparent, easy to debug, easy to re-run, give immediate error messages, give immediate output, and, above all, they are cheap (everybody has a spreadsheet package, legally or illegally).

Moreover, spreadsheets have a ready-to-use graphical interface, can easily import and export data to other software, have simple data base management facilities and built-in statistical packages, and can be programmed by using macro language. The macro languages particularly are very powerful. With macros, one can, in principle, do all the things one can do with source code written programs. But what makes spreadsheets so much more powerful than source code written programs is the combination of the sheet with the macros.

A spreadsheet is particularly useful for the description of phenomena in a two-dimensional framework such as: a horizontal groundwater model where the cells indicate, for instance, the water level or the pressure height; or a vertical groundwater model where the cells represent a vertical cross-section with pressure heights or water levels; or any network that one would want to describe in finite differences; or anything that one could compute in a table (unit hydrograph computations, flood routing, crop water requirements, etc.). The macros are then very useful to bring in the third dimension, which in many cases can be time. With a simple do-loop in the form of the macro \{FOR I, 1, 12, 1, subroutine\} a do-loop of 12 steps can be built into the program to recalculate the spreadsheet 12 consecutive times.
Table 1 Spreadsheet models for water resources modelling and planning.

<table>
<thead>
<tr>
<th>Spreadsheet tool</th>
<th>Developer</th>
<th>Reference</th>
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<tr>
<td>Groundwater models</td>
<td>Olsthoorn, 1984</td>
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<td>Helweg &amp; El-Khashab, 1986</td>
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<td>reservoir simulation, economical and multi-objective</td>
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<tr>
<td>Water resources analysis: hydrological models, database</td>
<td>Hancock &amp; Heaney</td>
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<td>Salt intrusion in estuaries: steady state models for</td>
<td>Savenije</td>
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<td>alluvial estuaries</td>
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<tr>
<td>Unsteady flow in open channels</td>
<td>Neis, Neis and Wigham</td>
<td>Neis et al., 1988</td>
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<tr>
<td>Reservoir operation and reservoir routing</td>
<td>Savenije, 1988</td>
<td>Savenije, 1994</td>
</tr>
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<td>WAFLEX, river basin simulation model</td>
<td>Savenije, 1988</td>
<td>Ketelaars, 1991</td>
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<tr>
<td>Water quality management, conservative, toxic and</td>
<td>Bartal, Memon and Haylon</td>
<td>Bartal et al. 1988</td>
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<tr>
<td>non-conservative substances</td>
<td></td>
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<tr>
<td>Data management for demand forecasting</td>
<td>Hall, Postle and Hooper</td>
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<td>Modelling non-point source pollution in watersheds</td>
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<td>Rainfall-runoff model for resources assessment in</td>
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<td>Water balance modelling: water budgets</td>
<td>Dexter &amp; Avery</td>
<td>Dexter &amp; Avery, 1990</td>
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<td>Urban water supply and demand models</td>
<td>Glenn</td>
<td>Glenn, 1991</td>
</tr>
<tr>
<td>Integrated set of modules for river basin planning:</td>
<td>N. de Melo Egidio</td>
<td>Melo Egidio, 1991</td>
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<td>irrigation, hydropower, water supply, trade-off analysis</td>
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<tr>
<td>Rainfall runoff model for resources assessment</td>
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<td>Leon, 1994</td>
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<td>quantity and quality</td>
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But perhaps the greatest advantage of spreadsheets is that they are flexible. It is easy to adjust a spreadsheet to a new situation. And flexibility is maybe the most important requirement of decision-support tools. Any person who is conversant with spreadsheets can easily make changes to a spreadsheet.
In this flexibility, however, also lies the greatest disadvantage of spreadsheets: they are not fool-proof. A spreadsheet models’ outcome is as reliable as the person who made it. There is no guarantee that the results are correct. Although one might say the same of fourth generation tools, there is clearly a difference. One may expect fourth generation models to be bug-free. Errors made with fourth generation tools should be the result of the input, not the software.

Other constraints of spreadsheet models are related to the relatively large memory requirements and that the run-time is high. However, with modern computers, both these constraints are rapidly disappearing.

In any case, spreadsheets should not be seen as a replacement for fourth generation tools. Spreadsheet models can be compared with the toolbox that we use for odd jobs in and around the house. Fourth generation tools compare to the expert whom we call in if the problem is too big for us to handle ourselves.

**WAFLEX — a flexible approach to water resource systems modelling**

The spreadsheet model WAFLEX is a water resource system simulation model which has been developed to respond to the above requirements. The equation of continuity and the fact that water flows from upstream to downstream are implicit in network functions. These network functions are relations between cells that can be copied to any location in the sheet to mould the network. Figure 1 is an example of a very simple network, consisting of a main stream with tributaries, inflow points and consumption points. Each cell in the river or canal branches (represented by the flow value) contains a network function which adds up the values encountered in the upstream adjacent cells. Depending on the orientation of the branch, the formula is different. If the orientation, for instance, is south, the cell contains the sum of the values of the cells directly west, north and east of it. More specifically, cell E6 in Fig. 1 contains the formula:

\[(+D6 +E5 +E7) \times \text{IF}(D6 +E5 +E7 < 0,0,1)\]

Cell E6 is part of an east-oriented branch which sums the values of the cells directly

![Fig. 1 Network structure of WAFLEX.](image-url)
west, north and south of it. The factor by which this sum is multiplied is the no-flow condition. If the sum of the three cells is negative (as is the case if the water demand is more than the availability, e.g. in cell D11), then the cell value becomes zero.

At diversions (bifurcations), allocation functions should be written which appear directly in the network, for example if a south-oriented branch splits in two:

\[
\begin{align*}
\text{South1} &= P \times \text{North} \\
\text{South2} &= (1-P) \times \text{North}
\end{align*}
\]

where \(P\) is the proportion of distribution. Of course any mathematical relation can be used instead of \(P\).

A macro is used to bring in the time dependency into the model. The macro is fairly simple; it is used to carry out subsequent time steps and to direct the model to the Main subroutine. The basic macro has the following form:

\[
\begin{align*}
\{ \text{FOR Cnt,1,Tot,1,Main} \} \\
\{ \text{QUIT} \} \\
\text{Main} \{ \text{CALC} \} \\
\text{Reservoir} \{ \text{CALC} \} \\
\{ \text{RETURN} \}
\end{align*}
\]

The macro uses range names that indicate cells in the spreadsheet as parameter names. In the first macro line, \(\text{Cnt}\) is the time step counter, \(\text{Tot}\) is the total number of time steps and \(\text{Main}\) is the range name of the first cell in the Main subroutine. The first thing that \(\text{Main}\) does is to carry out a spreadsheet computation through the Macro command \(\{ \text{CALC} \}\), which is intended to compute the release requirements (Req) to the reservoir (this is done in a separate window for demand computations). Subsequently, the program is directed to the Reservoir subroutine, where the reservoir release (Rel) is computed as a function of the reservoir operating rules. The final \(\{ \text{CALC} \}\) uses the reservoir release to compute the water allocation through the network.

**Reservoirs**

A reservoir can be easily incorporated into the network. A reservoir consists of three cells, an inflow cell (which can be the tail end of a branch), a storage cell and a release cell. The release cell acts as an inflow point to the downstream branch. The storage and release of the reservoir is determined in a Macro subroutine, which may look like this:

\[
\begin{align*}
\text{Reservoir} \{ \text{LET Stor1,Stor+Resin-Req} \} \\
\{ \text{LET Rel,Req} \} \\
\{ \text{IF Stor1 > Frc}\} \{ \text{LET Rel,Rel+Stor1-Frc} \} \{ \text{LET Stor1,Frc} \} \\
\{ \text{IF Stor1 < Urc}\} \{ \text{LET Stor1,Stor1+(1-Red)*Rel} \} \{ \text{LET Rel,Red*Rel} \} \\
\{ \text{IF Stor1 < Dsc}\} \{ \text{LET Rel,Stor+Resin-Dsc} \} \{ \text{LET Stor1,Dsc} \} \\
\{ \text{LET Stor,Stor1} \} \\
\{ \text{RETURN} \}
\end{align*}
\]
where: Req is the water requirement downstream of the reservoir; Rel is the release from the reservoir; Stor is the storage in the previous time step; Resin is the reservoir inflow; Storl is the storage in the next time step; Frc is the storage level of the flood rule curve; Urc is the storage level of the utility rule curve; Red is a rationing factor to reduce the release; Dsc is the dead storage requirement.

Figure 2 shows an example of the flood rule curve (FRC), the utility rule curve (URC) and the dead storage curve (DSC) as a function of time, together with a simulated storage fluctuation. The FRC is a hard boundary, meaning that the storage can never cross the curve. The DSC is a hard boundary as well, in the sense that it may never be crossed as a result of a release. The URC is a soft boundary which separates two zones in the reservoir where other operating rules are followed. The number of URCs is not limited, and neither is the operating rule related to the zone defined by it.

Demand computation

If one or more reservoirs exist in the network, the water requirement from the reservoir should be computed. This water requirement depends on both the demand for water and the availability of natural inflow. This computation is done in a "mirror-image" network which exists next to the "real" network. The mirror-image network is normally kept out of sight in a separate window. The mirror-image network is different from the real network in that it computes the required flow in upstream direction starting from the outflow requirement downstream.

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Fig. 2 Rule curves of multi-purpose reservoir.
APPLICATION OF WAFLEX

There are already numerous applications of WAFLEX. An educational version of WAFLEX was first developed in 1990 for the Conapu River basin in Trinidad (Savenije, 1994) as a demand-oriented system for the utilization of natural flows and regulated flows from Hollis Reservoir for water supply to Port-of-Spain and irrigation. Next, the model was applied by Ketelaars (1991) to the Incomati River basin with a multi-purpose reservoir with rule curves, hydropower, irrigation and water supply. Melo Egidio (1991) incorporated WAFLEX into an integrated modular planning tool which included: demand generation, irrigation planning, system simulation, yield and damage assessment and trade-off analysis.

Liu Heng (1993) applied the method to the North China Plain and incorporated the conjunctive use of groundwater and inter-basin water transfer. Workaferahu (1994) applied the method to a multi-reservoir system in the Awash River basin in Ethiopia. Mutale (1994) incorporated water quality into WAFLEX and applied it to the Kafue in Zambia, where the balance of total dissolved solids (TDS) contributed to the understanding of the water balance of the water resources system. Leon (1994) extended WAFLEX, further incorporating water quality aspects (both conservative and non-conservative substances) and salt intrusion, and applied it to the river basin and estuary of the Jubones River in Ecuador.

CONCLUSION

The principle of using a spreadsheet environment for the spatial variation in water resource systems and for data storage and retrieval is an excellent application of existing commercial software, which avoids complicated programming otherwise required under traditional programming languages. Also the readily available facilities for graphics representation save considerable programming effort. The amount of macro language code can thus be limited to the absolute minimum, which pays off directly, not only through the limited developing time required, but even more so in the limited time required for debugging.

Experience has shown that the spreadsheet approach to river basin modelling can be readily and successfully applied to a wide range of hydrological and water use environments, within a very limited time.

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