A decision support system for the operation of a reservoirs system

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Abstract

This paper shows a decision support system that allows one to obtain optimum operation rules for a reservoirs system of a hydrological basin located at the north of Mexico. This basin is characterized by notorious periods of water scarcity. The decision support system consists of a geographic information (GIS) module and a database that holds descriptive information about weather and hydrometric stations that are located inside and around the hydrological basin, as well as historical information recorded in each one of the stations and in the reservoirs. The system incorporates an optimization model, based on linear programming, to obtain the optimum operation rules. The objective function seeks to maximize the water volume that is released and used in irrigation agriculture. This function is subject to constraints related to water availability in the basin, the hydraulic performance of the reservoirs (evaluated through continuity equations), storage capacity of the reservoirs, release limits and monthly demands given as a percentage. The operation rules can be obtained either by considering a constant release, a release as a function of the inflow or as a function of the inflow and storage. This computer system offers a great flexibility to analyze several alternatives in order to take the best decision to operate the reservoirs.

1 Introduction

Currently, many decision support systems for water resources management combine geographic information systems (GIS), database tools and mathematical modeling in order to analyze problems related to water resources, assess different scenarios and take the best decisions. The objective of the work shown on this
paper was to develop a decision support system to analyze and evaluate several options to operate a reservoirs system, by using a linear programming technique. The computer system developed also provides GIS capabilities and a database with climatic and hydrometric information of the study area.

2 Study area description

The study area is the Nazas river basin, which belongs to hydrological region 36 Nazas – Aguanaval. This basin that is located at the north of Mexico, has notorious periods of water scarcity and is characterized by an arid climate; the average annual precipitation is around 400 millimeters. Figure 1 shows the location of the study area inside the Mexican Republic and a zoom that shows the states among which the study area is divided. The main economical activity in the area is the irrigation agriculture.

Figure 1: Location of the Nazas river basin in the Mexican Republic.

Figure 2 shows the hydrography, and the location of the reservoirs and agriculture areas inside the mentioned basin. The most important hydraulic infrastructure is made up by two reservoirs, Lázaro Cárdenas and Francisco
Zarco, which supply water to irrigation district 017. This district is divided in two agricultural zones, one located downstream of the Lazaro Cardenas reservoir, and the other one located downstream of the Francisco Zarco reservoir.

Figure 2: Hydrography, and location of reservoirs and agriculture areas in the Nazas river basin.

3 Methodology

3.1 Optimization model

Figure 3 shows the schema formed by the elements that compound the system being analyzed, and also describes the way they are connected to each other. The methodology used to determine the optimum operation policy for the reservoirs system of the Nazas river basin was based on the optimization model SISMAPRE [4], which uses a linear programming technique. This model was modified to get a model that represented the operation of the system shown in figure 3. The basic information considered to formulate the mathematical model was the storage capacities of each reservoir, monthly inflow volumes, monthly net evaporation (measured in mm) in each reservoir, and monthly demands (given as a percentage) of the irrigation district 017 which were obtained from historical records of water releases.
The objective function of the mathematical model seeks to maximize the water volume that is allocated to the irrigation district 017 to meet its demands for agriculture. With this in mind, the objective function is given by the following expression:

$$\text{Max} \sum_{i=1}^{NP} \sum_{t=1}^{NA} \left( \text{EXTA}_{i}^{t} - \sum_{j=1}^{12} D_{j,t}^{i} \right)$$

(1)

where:

- $NP$ is the number of reservoirs in the system being analyzed (known data).
- $NA$ is the number of years considered in the planning horizon (known data).
- $i$ is an index used to represent each reservoir.
- $t$ is a sequential index used to represent a specific year with hydrometric data.
- $j$ is an index used to represent each month of a given year $t$; $j=1$ represents the month in which a decision is made about what volume to extract for the next agricultural season. In this study, the decision month was October (known data).
- $\text{EXTA}_{i}^{t}$ is the annual volume released from the reservoir $i$, in the year $t$, and allocated to the irrigation district 017 (decision variable).
- $D_{j,t}^{i}$ is the overflow occurred in the reservoir $i$, in the month $j$, in the year $t$ (decision variable).

The objective function given in equation 1 is subject to the following constraints in each reservoir:

- Continuity equations
- Stationary operation policies
- Storage capacities
- Minimum and maximum release limits

Furthermore, the operation policy is subject to two constraints: the water volume stored at the beginning of the agricultural season and the inflow received in each reservoir at the preceding annual period. Since the release is then defined as a function of the inflow previously received and the current storage, the operation rules can be adjusted to periods of scarcity, normality or plenty of water resources. To obtain the operation policy as a function of the preceding inflow, allocation percentages are computed for three ranges of annual inflow, these ranges are defined by the quantiles 0.33 and 0.66 (indicated as \( V_1 \) and \( V_2 \) respectively in the equations below) of the probability distribution function that characterizes the inflow. These inflow ranges allow one to classify all the years with inflow data in three groups (dry, normal and humid years), each group having an equal number of elements. To obtain the water allocation as a function of the stored volume at the beginning of the agricultural cycle, a proportion of this volume, that will be allocated in a given year, is specified through a variable \( c(S_{i,t}) \). According to the above explained, the constraints are the following:

\[
\text{EXTA}_i^t = c\left(S_{1,t}^i\right) + \alpha^i + \beta_1^i \sum_{j=1}^{12} Q_{j,t-1}^i, \quad \text{if } \sum_{j=1}^{12} Q_{j,t-1}^i < V_1^i
\]  
\[
\text{EXTA}_i^t = c\left(S_{1,t}^i\right) + \alpha^i + \beta_1^i V_1^i + \beta_2^i \left( \sum_{j=1}^{12} Q_{j,t-1}^i V_1^i \right), \quad \text{if } V_1^i \leq \sum_{j=1}^{12} Q_{j,t-1}^i < V_2^i
\]  
\[
\text{EXTA}_i^t = c\left(S_{1,t}^i\right) + \alpha^i + \beta_1^i V_1^i + \beta_2^i (V_2^i - V_1^i) + \beta_3^i \left( \sum_{j=1}^{12} Q_{j,t-1}^i - V_2^i \right), \quad \text{if } V_2^i \leq \sum_{j=1}^{12} Q_{j,t-1}^i
\]

where:

\[
F_{Q_{\text{annual}}}^1(1/3) = V_1^i \quad \text{and} \quad F_{Q_{\text{annual}}}^1(2/3) = V_2^i
\]

and:

\( Q_{j,t-1}^i \) is the inflow volume that the reservoir \( i \) receives, in the period of time \( j \), in the year \( t-1 \) (known data).
$F^l_{\text{annual}i}$ is the inverse transformation of the probability distribution function that fits the annual inflow of the reservoir $i$ (known data).

$c_i(S_{1,i})$ is a storage coefficient. It denotes a proportion of the volume stored in the reservoir $i$, at the beginning of the agricultural season, to be allocated (known data).

$a_i$ is the base volume, or value at the y-axis (ordinate), where the allocation policy begins (decision variable).

$\beta^l_1$ is the water allocation per each unit of inflow received in the preceding annual period, $Q^l_{\text{annual}i-1}$, for inflow volumes lesser than $V^l_1$, that is, it is slope of the first segment of the allocation policy (decision variable).

$\beta^l_2$ is the water allocation per each unit of inflow received in the preceding annual period, $Q^l_{\text{annual}i-1}$, for inflow volumes greater than or equal to $V^l_1$ but lesser than $V^l_2$, that is, it is slope of the second segment of the allocation policy (decision variable).

$\beta^l_3$ is the water allocation per each unit of inflow received in the preceding annual period, $Q^l_{\text{annual}i-1}$, for inflow volumes greater than or equal to $V^l_2$, that is, it is slope of the third segment of the allocation policy (decision variable).

The linear programming model above described is solved by calling some functions of the Lingo 7.0 library, so it is necessary to have this software installed in order to be able to use the decision support system. The result of the optimization process is the optimum operation policy for the system of reservoirs of the Nazas river basin. The optimum water allocation is the sum of two figures: the allocation corresponding to the current storage in each dam, at the time when the decision is made, and the allocation corresponding to the inflow received in the previous year. In other words, the optimum release will depend on the volume stored in each reservoir and on how the preceding year was: dry, normal or humid. The storage coefficient, as well as the parameters (slopes) that define the policy, are computed during the optimization process, therefore they are guaranteed to be optimum [5].

3.2 Geographic information system (GIS)

The maps considered in the GIS module were hydrologic basin and regions, location of hydrometric and weather stations, hydrography, location of dams, and states that are included in the study area. A design was made to define the graphical user interface, the GIS capabilities that the system would offer, and an interface to set up the system and add new maps and data. Also, functions related to maps display were considered: zoom in, zoom out, pan and identify.

3.3 Database

A database was designed to hold climatic and hydrometric data of the stations inside the hydrological region and those located in the neighborhood of the study
area. The climatic data was daily measurements of rainfall and evaporation recorded at each weather station; this information was obtained from the ERICII [1] and SICLIM [2] systems. The hydrometric data was obtained from the BANDAS [3] system; this information consisted of daily average flow measured at each station. The database module was designed to provide several options to query the data and extract it in the most common formats required by final users.

4 Implementation

The graphical user interface of the decision support system, the mathematical formulation and the functions for querying the database were developed with Visual Basic 6.0, as this programming language provides several built-in components to develop applications, and the interface to communicate with other software is easy to use. Geographic information capabilities were implemented with an ActiveX component called Map Objects, which allows to insert geographic objects into an application. As explained before, the linear programming model is solved by calling functions of the Lingo 7.0 software library.

Figure 4 shows the main dialog window of the decision support system. This window is made up by a main menu, a tool bar, a canvas where the map of the hydrological region 36 is displayed, a frame to turn the available maps on and off, an area to show the coordinates (longitude, latitude) of the pointer, and a status bar to indicate tasks execution.

![Figure 4: Main dialog window of the decision support system.](image)

The system permits to query the database once a set of weather or hydrometric stations has been selected by using a logical condition. This condition can involve one or many attributes of those that describe each station on the
database. Thus, it is possible to submit a query like this: "State = ‘Durango’ AND years_with_rainfall_data > 20 AND rainfall_missing_data_percentage < 10". Some criteria by which the stations can be selected are:

- Period of time with data
- Key
- Missing data percentage
- State and hydrological basin

The main dialog window of the optimization module is shown in Figure 5. At starting, this window displays a list of the reservoirs located in the Nazas river basin and the data file associated to each; it is a text file that contains the data required in the model, which was described in section 3.1. The second section of the dialog window shows the available options to obtain the operation policy: either constant release, as a function of the inflow, or as a function of the storage – inflow. The third section shows the period of time with data for both reservoirs and two lists that permit to specify the initial and final year to carry out the optimization process. When choosing an operation policy that is a function of the storage – inflow, a section is shown to specify the maximum and minimum release limits to be used in the linear programming model.

![Figure 5: Dialog window of the optimization module.](image)

The results are shown in an Excel book with two worksheets, one for each reservoir. Each worksheet shows the following results:

- Optimum and historical annual releases
- Optimum and historical monthly average releases
- Operation policy (graph and parameters)
5 Results

This section shows the results produced by the decision support system considering the following scenario:

- Both reservoirs are working in a combined way
- Two operation alternatives: without release limits (1) and with release limits (2)
- An operation policy as a function of the stored volume and the inflow received in the preceding year
- Period of time analyzed: from October, 1968 to September, 2000

The results obtained for both alternatives (without and with release limits) show that the optimum release is lightly greater (3 and 5 % respectively) than the historical average annual release in each reservoir for the period analyzed. The limits used in alternative 2 were the historical minimum and maximum volumes extracted from the reservoirs. The average annual overflow occurred in alternative 1 was 58 and 68 Mm³ for Lázaro Cárdenas and Francisco Zarco reservoirs respectively; in alternative 2 the overflow happened to be 67 and 70 Mm³ respectively. These results are showed in table 1; in the first column, “Alt.” stands for “Alternative”, and C(S), in the third column, is the storage coefficient.

<table>
<thead>
<tr>
<th>Alt.</th>
<th>Reservoir</th>
<th>C(S)</th>
<th>Release limits (Mm³)</th>
<th>Average annual release (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>1</td>
<td>L. Cárdenas</td>
<td>0.707</td>
<td>1108.39</td>
<td>1061.29</td>
</tr>
<tr>
<td></td>
<td>F. Zarco</td>
<td>1.000</td>
<td>1117.24</td>
<td>1054.28</td>
</tr>
<tr>
<td>2</td>
<td>L. Cárdenas</td>
<td>0.298</td>
<td>1091.80</td>
<td>1061.29</td>
</tr>
<tr>
<td></td>
<td>F. Zarco</td>
<td>1.000</td>
<td>1111.30</td>
<td>1054.28</td>
</tr>
</tbody>
</table>

When comparing the results obtained to the historical performance of the reservoirs, it can be seen that the optimum average monthly releases of alternative 2, for both reservoirs, follow the same trend shown by the historical average monthly releases. Figure 6 shows these graphs for both reservoirs. It means that the mathematical model appropriately represents the performance of the water bodies under the hydrological conditions analyzed.
Figure 6: Optimum and historical average monthly releases of the reservoirs of the Nazas river basin.

6 Conclusions

According to the results, it can be said that the mathematical model developed is suitable to represent the hydraulic performance of the reservoirs system of the Nazas river. The optimum values have the same tendency shown by the historical ones. On the other hand, the optimum releases obtained with the system proposed are lightly greater than the historical values, it means that this difference could be released and used to enlarge the irrigated areas or used for other purposes.

The decision support system described allows one to analyze the reservoirs, alone or working in a combined way, under different alternatives in order to take the best decision to operate them. Finally, the incorporation of GIS capabilities and a database allowed to manage in a better way the geographic information and data that were required in the model. These characteristics turn this system into a valuable tool for decisions making in water resources management.

References