CONJUNCTIVE USE OF A MODEL AND DECISION SUPPORT TOOL FOR WATER RESOURCES PLANNING IN THE CAIA RIVER CATCHMENT, PORTUGAL

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ABSTRACT
Hydrological simulation models generate predictions and scenarios of water quality and water quantity that are potentially useful to resource managers, policy makers, stakeholders, and other end-users. Realizing this potential, however, requires that model outputs be suitably transformed, and combined with information from other sources. Decision support systems (DSS) are well-suited to analysis of the complex interactions between physical, economic, and social factors in environmental problems, and thus represent a link between modelling and management. We will explore some of these issues in the context of a study involving the application of a catchment and groundwater model together with a multicriteria decision support tool to an agricultural region in southern Portugal, the Alentejo region near the Spanish border. The study was performed in the framework of a European Union funded project (MULINO) aimed at improving decision making in catchment scale water resources management, in compliance with the EU's Water Framework Directive.

RÉSUMÉ
L'utilisation de modèles hydrologiques permet d'effectuer des prévisions, relatif à la quantité et la qualité de l'eau, pouvant être potentiellement très utiles pour les autorités compètent dans la gestion des ressources hydriques. La réalisation de cette potentialité requiert toutefois que les résultats de ces modèles soient manipulés et combinés avec des sources d'informations complémentaires. Les systèmes de support d'aide à la décision (DSS) sont structurés de manière à permettre l'analyse des interactions entre les facteurs physiques, économiques et sociaux caractérisant ainsi les problèmes environnementaux, autrement dit, ces systèmes représentent une liaison entre les problèmes de modélisation et de gestion. Nous analyserons ces thèmes dans le contexte d'une étude qui consiste en l'application d'un modèle hydrologique aux bassins versants et aux eaux souterraines secondé d'un système de support d'aide à la décision appuyé sur les analyses multicriteria. Ces systèmes seront appliqués dans la région agricole de l'Alentejo, située dans la partie méridional du Portugal. L'étude fut réalisée dans le cadre d'un projet de l'Union Européenne (MULINO) dans le but d'améliorer le processus décisionnel dans la gestion des ressources hydriques à l'échelle des bassins versants, en conformité avec les directives européennes concernant la gestion de l'eau.

1. INTRODUCTION

The 780 km^2 Caia River catchment is located in a region of South Portugal, the Alentejo, near the border with Spain and it is a tributary of the Guadiana River, one of the major Iberians rivers. Environmentally, the Alentejo is a region where extreme climatic conditions and insufficiently fertile land have limited in the past the development of a competitive agriculture. Furthermore, it owes its economic and social particularity to the dominant large landowner system of extensive monoculture. Extensive agriculture and pastures are still the basic economic activities. Land use production makes little use of crop rotation and large parts of its territories are still not sufficiently exploited.

The construction of a dam 30 years ago caused a strong impact on human activities and environmental dynamics. The reservoir created by the Caia dam stimulated in the last 30 years the conversion of the agricultural system from rainfed farming to intensive irrigated production, with the total irrigated area now encompassing around 130 km^2. This reservoir, with a total capacity of 203 Mm^3 (live storage: 192.3 Mm^3, unusable capacity: 10.7 Mm^3), is the source of extraction of water for the different uses. In this catchment multi-purpose water management is a necessity. Although the main water use is associated with agriculture (91.2%), which is also the main land use in the region, there are two other significant water uses in the catchment: industrial (8.7%) and public supply (0.1%) for the town of Elvas and several villages. Furthermore, water uses such as those related to recreational activities (sailing and fishing) and ecological interests (minimum vital flow) are relevant from a socio-economic viewpoint. The increasing competition amongst these different sectors underlines the problem of scarcity and irregularity (seasonal or interannual) of available water resources, rendering the management of water quantity and the preservation of water quality very significant issues.

In a context of water shortage and increasing water demand it is important to evaluate the socio-economic and environmental impacts of new water management strategies. One of the keys to stimulating socio-economic growth is to design an integrated water resources management system for the region. An integrated approach is needed to describe the complexity of the problem at hand, as alternative water management policies may interfere with activities based on traditional rural land organization. In this study we will compare and evaluate three options for the allocation and distribution of water on the catchment: (1) the actual situation, with a single dam and reservoir; (2) a possible future dam and reservoir, hydraulically connected to the existing reservoir; (3) the same future dam and reservoir, but not connected to the existing reservoir. These alternatives are also evaluated under a realistic future climate scenario generated from a meteorological analysis.

The problem formalization characterizing the Caia case study was set up by defining the DPSIR chain (driving forces, pressures, state, impacts, responses) that identifies the relevant socio-economic and environmental indicators. We defined as driving forces agricultural production and the management of the dam, as pressures the water needs for urban, industrial, agricultural, and recreational uses, and as states the irrigable area, the reservoir exploitation, the average reservoir level and its variability, the efficiency of the system, the total costs, the farmer risk income, and the conflicts between users. The actors or stakeholders involved in the decisional process included INAG (Water Institute for Portugal), private farmers belonging to the Irrigation Board, and local municipalities.

The hydrological model SWAT (soil and water assessment tool) and an optimization module for reservoir regulation are used to generate the water balance results corresponding to the different climate change scenarios and dam operation options. We describe the various steps in the model–DSS process — assembling the available data for model input, processing the simulation results into appropriate criteria (parameters) for the DSS, setting up the analysis and evaluation matrices, assigning weights, conducting sensitivity analyses — and the difficulties faced along the way, in particular with regards to data quality and subjectivity.

2. DESCRIPTION OF TOOLS

2.1 Hydrological model

The hydrological model adopted in this study is SWAT (Soil Water Assessment Tool) developed by Arnold et al. (1994) for the USDA Agricultural Research Service (ARS). SWAT is a continuous time model that operates on a daily time step. Although the model operates at this step it is intended as a long-term yield model and is not capable of detailed, single-event, flood routing. The objective in developing SWAT was to predict the impact of land management practices on water, sediment and agriculture chemical yields in large ungaged basins. To satisfy this objective, the model is (a) physically based, (b) uses readily available inputs, (c) is computationally efficient to operate on large basins in a reasonable time, and (d) is a continuous time model and is capable of simulating long periods for computing the effects of management changes. The components of SWAT are: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. We will deal specifically with the components related to the estimation of the water balance, such as hydrology and weather.

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1,n}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad [1]$$

where SW_t and SW_0 are the final and initial soil water content, R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, w_{seep} is the amount of water entering the groundwater zone from the soil profile on day i, and Q_{gw} is the amount of return flow on day i. The components of Equation 1 are predicted separately for each hydrologic response unit (HRU). The hydrologic response units are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations that enables the model to reflect differences for various crops and soils. For the SWAT model these units are obtained by overlaying land use and soil maps.

The implementation and application of the numerical code has been supported by using the ArcView graphical interface (AVSWAT2000) developed by Di Luzio et al. (2001). This interface is configured as an extension that allows the use of all the functions and potentiality of that geographical information system in helping in the delineation and characterization phase and in the loading of the weather data for the study site.

2.2 Decision support system

The decision process as described by Simon (1960) and implemented in the MULINO project DSS (mDSS) is subdivided into three phases: conceptual phase (identification and decomposition of the problem); design phase (design of options, identification of indicators and criteria, prediction of outcomes); and choice phase (selection of the “best” option, sensitivity analysis). On the basis of this process, the multicriteria decision analysis starts with problem structuring during which the problem to be solved is explored and available information is collected. Alternative options are defined and criteria aimed at assessing their feasibility are identified. This is the interaction phase between the DSS and SWAT, i.e., the hydrological information that can contribute to the analysis matrix is identified. In the next step the performance (row performance) of the options is scored and an analysis matrix (AM) is constructed. Furthermore, the same options and their relative performances with respect to the selected criteria can be evaluated according to different alternative scenarios representing hypothetical future events such as land use or climatic changes.

Passing from the analysis matrix to the evaluation matrix (EM), the scores are transformed to values (relative performance) on a uniform scale so that the assessment can be made in a standardized manner. This procedure requires the definition of a value function including human judgements (decision maker's preferences) in the mathematical formulation, and translation of the performance of an option into a value score, which represents the degree to which a decision objective is matched. In order to aggregate the partial preferences describing individual criteria into a global preference and then rank the options, the mDSS includes different decisional rules such as simple additive weighting (SAW), analytic hierarchy process (AHP), order weighting averaging (OWA), and an ideal point method (TOPSIS). The description of the decisional rules and of the different value functions used in our study will be given in a later section on the mDSS implementation.

The sensitivity analysis in the choice phase evaluates how robust (or weak) the selected option is to eventual bias or small changes in preferences expressed by the decision maker. As concerns this point the mDSS includes two different approaches: the most critical criterion and the tornado diagram. The former identifies the criterion for which the smallest change of current weight may alter the existing ranking of options, while the latter compares graphically the chosen option with any other one and shows the ranges within which the parameters may vary.

3. DATA SET-UP

3.1 Climate data and future scenario

For the climatology of the basin, the available data is represented by monthly values of precipitation (mm) and maximum and minimum temperature (°C). This monthly data, supplied by the Portuguese Hydrological Survey for the period 1960 to 1990 for 17 gages located within the watershed, are not in a form compatible with the SWAT model, which requires either actual daily values or averaged monthly data obtained from multi-year records. In this second case, which corresponds to our situation, it is however necessary to calculate a set of statistical parameters such as the probability of a wet day following a dry day in any given month or the average number of days of precipitation in a month. To estimate these statistics we used a dataset of daily values recovered from the literature, in particular the NCEP-NCAR analyses (National Centers for Environmental Prediction and for Atmospheric Research, respectively). These daily datasets for precipitation and temperature were considered representative of the entire Caia basin (equivalent to one gage for the whole watershed). From these time series it was then possible to calculate the statistics related to precipitation and maximum and minimum temperature. The statistics related to maximum and minimum temperature were then used to generate daily values referring to the weather generator implemented into the SWAT model and based on the weakly stationary generating process described by Matalas (1967), while those related to precipitation were used to generate synthetic daily precipitation series for each rainfall gage of the study site implementing a weather generator developed by Cau et al. (2003) and based on the Markov chain-skewed generator proposed by Nicks (1974). The generator works in two steps: first it determines if the day is wet or dry, then a skewed distribution is used to generate the precipitation amount. The sum of the daily precipitation of each month of each year is scaled to match the monthly registered rainfall for each station.

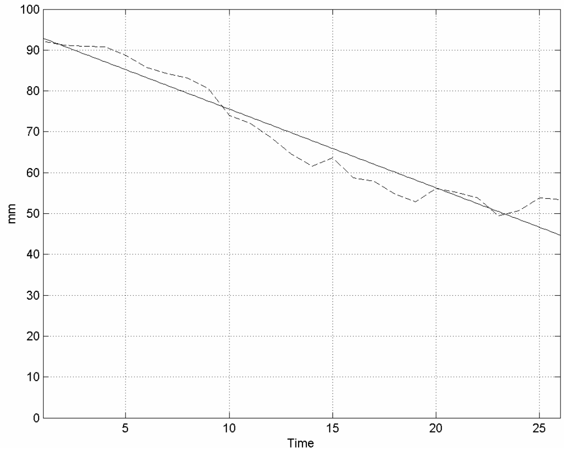

Figure 1. Example of linear extrapolation procedure for the monthly cumulative value.

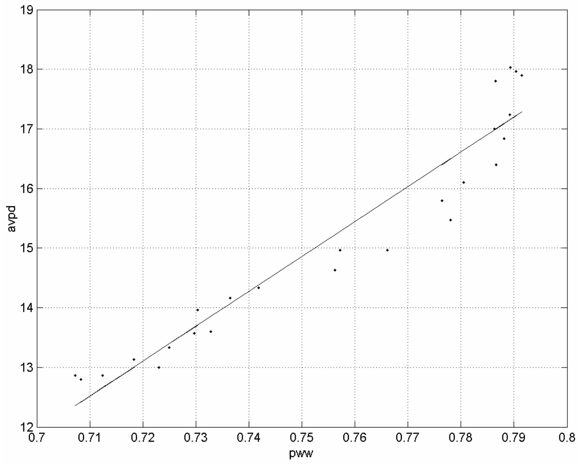

Figure 2. Example of scatter plot between the PWW (probability of a wet day following a wet day) and the AVPD (average number of days of precipitation per month).

For the Caia decisional case a future climatic scenario has been forecast on the basis of a meteorological analysis carried out in accordance with a daily dataset from 1948 to 2002 and recovered from the literature (NCEP-NCAR analyses). First we start comparing, for each month of the year, the averaged cumulative value of precipitation obtained from meteorological daily data (lower spatial resolution) with those obtained referring to available observations (higher spatial resolution). In order to take into account of a systematic underprediction shown during the wet period (from January to April and from October to December) and an overprediction during the dry period (from May to September) of the former (meteo data) with respect to the latter (observed data), we defined two correction factors. The values of these factors are 1.15 (wet) and 0.56 (dry).

The second step was, referring to the meteorological daily dataset, to calculate for each month the moving average considering 30 years to use in leading the calculation and 1 year as skipping step. On the basis of the better correlation, we extrapolated from this sample of averaged cumulative values with a linear (Figure 1) or log function the predicted cumulative value to input into the weather generator. As a result of this first part of the meteorological analysis we inferred that the cumulative value of precipitation averaged on a yearly step will probably endure a reduction around the 10%.

The second part of this study was devoted to analyze those parameters describing the precipitation distribution. In particular, as concerns the other required statistical parameters (i.e, the probability of a wet day following a dry/wet day in any given month or the average number of days of precipitation in a month) we proceed as follow: we predicted the value of a variable (eg, the probability of a wet day following a wet day) adopting the same procedure described above for the cumulative value, then, once having estimated the correlation (0.65 was established as a threshold value) between this chosen variable and the others (eg, the average number of days of precipitation per month) we calculated the value of these latter entering into the scatter plots (Figure 2) with the predicted value of the former one. The consistency of the described procedure was verified comparing the values inferred from the scatter plots with those obtained by means of the extrapolation procedure. Finally, in case of an absence either of a marked trend or of an acceptable correlation, we referred to the mean value. The evidence emerging from the second part of this climatic analysis was that the number and the length of the precipitation events is decreasing as inferred from the reduction both of the probability of a wet day following a wet day and the probability of a wet day following a dry day.

3.2 Topographic, land use, and soil data

The delineation and the topographic characterization of the watershed was obtained from a DEM with a resolution of 100 m derived by interpolating a 1:25 000 topographic map with 10 m contours. The average elevation of the catchment is 334 m with a range from 180 m to 997 m and the terrain is gently sloping (0-5%) except in the upper reaches (Serra de São Mamede) where slope angles can be as high as 35%.

The land use characterization of the watershed was made by aggregating the classification of a more detailed CORINE (Coordinated Information on Environment) vector map at 1:100 000 resolution. The resulting land use classes are: 56% "generic agricultural land" (AGRL), 31% "deciduous forest" (FRST), 5%" mixed forest" (FRSD), and 3% "water" (WTRN). As shown in Figure 3 (left plot), agricultural production is mostly concentrated in the southern portion of the catchment, and it consists of rice, maize, tomato, and other crops.

Regarding the procedure adopted to define a soil map as required by AVSWAT, first, thanks to the support provided by soil scientists familiar with the Caia site, we found the match between an initial FAO classification with the soil taxonomy (Figure 3, right plot). We then derived, from the percentage of clay, silt, and sand and using classical pedotransfer functions, other soil properties such as the available water capacity (AWC) and the hydraulic conductivity. From the value of the hydraulic conductivity we classified each map unit according to Soil Conservation Service (SCS) hydrologic groups A, B, C, or D on the basis of which SWAT can calculate the surface runoff using the curve number (CN) method. In this way we achieved for each map unit its physical parameterization. A more rigorous approach would have required the knowledge of soil profiles by means of field studies, including the depth and possible stratification of the rooting zone. Given this lack of information, we hypothesized a single soil layer with a depth of 1 m or 1.5 m as described in the next section.

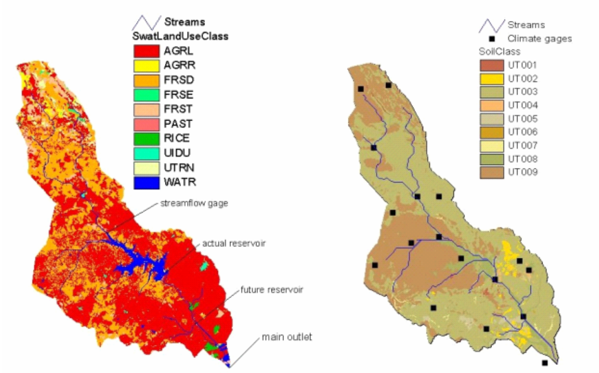

Figure 3. The Caia land use (left) and soil (right) maps showing also the location of the streamflow gage within the watershed, the actual and future reservoir, the main outlet of the watershed, and the position of temperature and rain gages (black squares).

3.3 Hydrological data

The hydrological observations on the Caia site consist of a set of monthly discharge values for the period 1960-1990. This set of data, provided by the stream flow gage located within the watershed, was divided into two 15-years series, with the first half (1960-74) used to calibrate the model and the second (1975-90) used to assess the reliability of the calibration. The calibration-validation procedure was carried out referring to average annual conditions and computing the widely used goodness of fit measure based on the error variance, i.e., the modelling efficiency index E proposed by Nash and Sutcliffe (1970):

$$E = 1- \sigma_\varepsilon / \sigma_o \quad [2]$$

calculated on a monthly step, where σ_ε and σ_o are the error variance and the variance of the observations, respectively.

The main parameters involved in the calibration procedure are those having both high uncertainty and a strong influence on evapotranspiration, percolation, and recharge of the aquifer in the sense of the model results being quite sensitive to changes in these parameters. By these criteria the selected parameters were the maximum rooting depth of the soil profile (SOL_ZMX) and the available water capacity of the soil (SOL_AWC).

Table 1. Soil parameter values for the four configurations.

Configuration	SOL_ZMX	SOL_AWC
1 (starting point)	1.0	default
2	1.5	default
3	1.0; 1.5	default
4	1.0	+ 0.01

As reported in Table 1, modifying first the values of the maximum rooting depth we defined three different configurations. For the default configuration we hypothesized an equal value of 1 m for all five subbasins subtended by the streamflow gage, then we increased this value to 1.5 m for the second configuration, and for the third configuration we set different values for different subbasins; in particular we selected values of 1 m and 1.5 m for upland and low-lying subbasins, respectively.

Table 2. Performance measures calculated over the calibration period (1960-74).

Config.	E	Observed [mm]	Simulated [mm]
1	0.65	158.4	208.9
2	0.63	-	161.0
3	0.66	-	174.4
4	0.65	-	167.8

Table 3. Performance measures calculated over the validation period (1975-90).

Config.	E	Observed [mm]	Simulated [mm]
4	0.22	136.0	145.9

From the comparison of model efficiency (Table 2) it emerged that the best performance is achieved for the third configuration. Moreover, analysis of the average values underlines that for this configuration simulated runoff is still overpredicted with respect to the observed one. To obtain a closer match between observed and simulated runoff, in the fourth configuration an equal increment for the five subbasins of 0.01 of the available water capacity parameter was imposed. The result was that on one hand the model overprediction was acceptable compared to the possible errors associated with observations that are characterized by some anomalies (e.g., absence of streamflow in 1973 despite non-negligible rainfall) and on the other hand the value obtained for model efficiency indicates that the defined set of model parameters may be considered representative for the physical characteristics of the catchment. For this last configuration we show the monthly rainfall-runoff plot (Figure 4) where it is seen that the hydrologic trend computed by the model generally conforms with the observations despite some disagreement in the timing, shape, and peaks of the observed and simulated hydrographs.

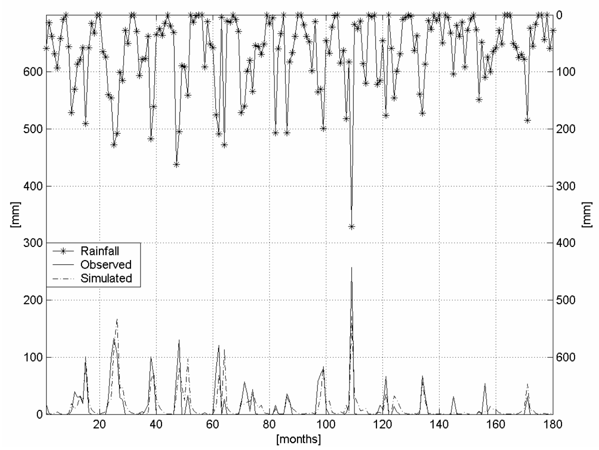

Figure 4. Comparison on a monthly basis for the calibration period (1960-74) of observed and simulated streamflow for the fourth configuration.

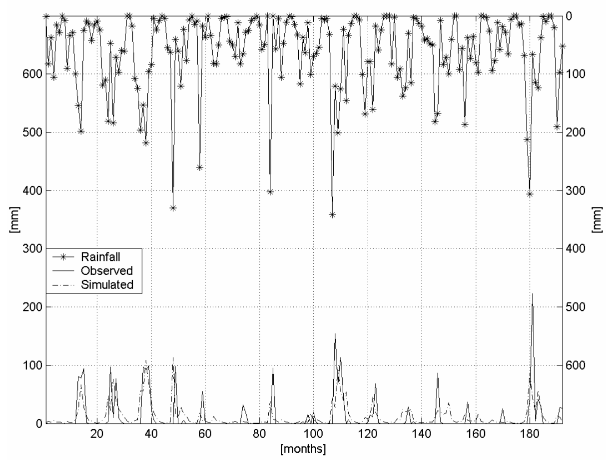

Figure 5. Comparison on a monthly basis for the validation period (1975-90) of observed and simulated streamflow for the fourth configuration.

The reliability of the calibration was then evaluated referring to the second 15-year time series. The results obtained (Table 3) show a reduced model efficiency and yet comparable values of averaged yearly streamflow to those obtained in the calibration phase. Figure 5 shows how the disagreement between the observed and simulated streamflow data is evident during low flow periods when the observed measurements are practically zero.

It can be remarked, with regard to the calibration-validation exercise, that more thorough model parameter optimization for this study would require a more consistent spatio-temporal dataset including measurements of soil depth, groundwater well observations, etc, and that the quality and reliability of this data (including uncertainty estimates) should be taken into account in the implementation of the decision support system. For instance, the available monthly streamflow data provided by the Portuguese Hydrological Survey did not include the separation of surface runoff and base flow components from the discharge hydrograph and the assessment of the alpha base flow recession constant describing the slope of the streamflow decline after a recharge event. Furthermore, for a more detailed implementation of the model-DSS methodology, streamflow data for the entire Caia watershed will be essential (i.e., a gaging station should be installed at the outlet of the catchment), rather than the calibration based on streamflow data for only 30% of the catchment as performed here.

4. MODEL RESULTS AND DSS IMPLEMENTATION

Once a satisfactory calibration was obtained, we focused on the entire watershed (including the dam) and generated comparable alternatives representing different water management practices as suggested by the DSS analysis matrix. The output provided by the SWAT model (the streamflow value at different outlets located within the watershed) was then used to implement an external optimization module describing the reservoir operation. In particular, we simulated the filling (during deficit periods) and depletion (outflow/spillway during surplus periods) process of the reservoir, solving by finite differences with a monthly step equation:

$$Q_i(t) - Q_o(t) - Q_s(t) = dW(t)/dt \qquad [3]$$

where Q_i is the flow rate into the reservoir provided by the SWAT model, Q_s is the spillway flow during the surplus period, W(t) is the storage volume of the reservoir, and Q_o is the outgoing flow rate from the reservoir which is the sum of four components: the domestic, industrial, and agricultural water use and the volume of water required in order to guarantee the minimum vital flow. We estimated the domestic water use on the basis of the population of the city of Elvas and other villages, hypothesizing a unit water requirement of 300 l/day. For the industrial water supply we followed the indications reported in previous studies carried out by the Portuguese Institute of Statistics which evaluated this demand as 8.7% of the current averaged water available. The industrial and domestic supply was assumed equal for each month over the entire simulation period, while for agriculture we embedded a monthly irrigation coefficient to distribute the water requirement in accordance with lower precipitation during the summer period. The volume of water needed to satisfy the minimum vital flow was evaluated as 50% of the long term average streamflow occurring in the dry season (from June to September). The water management module was implemented to evaluate the performance for each considered alternative under the actual and supposed future scenario. The target of the analysis is to achieve the maximum water volume for agricultural use with the constraint that the deficit of the reservoir should always equal zero and with a fixed equalizing capacity. In other words this problem consists in the verification of the established capacity and the determination of a compatible outgoing flow rate trend.

We begin by simulating the water balance for the whole catchment subtended by the main outlet and evaluating the streamflow at the reservoir location for the actual and hypothesized future dams as indicated in Figure 3. The location of this latter dam has been defined with the constraint that the subtended area should be hydraulically disconnected from that defined by the existing one. The capacity of the hypothetical new reservoir was estimated at 60 Mm^3 by topographic analysis of the digital terrain data and in particular referring to the hypsographic curve calculated by a tool based on an automatic procedure included in the watershed delineation module of the SWAT model. The resulting components of the hydrologic budget on an averaged monthly basis (Table 4) are equal to 52.1 mm for precipitation, 26.7 mm for evapotranspiration, and 23.3 mm for streamflow (actual scenario) at the main outlet. We thus obtain a percentage evapotranspiration of 51% and a monthly minimum vital flow estimated at 5.8 mm.

Table 4. Monthly water balance for the actual(1960-90) and future scenario (1990-2050) at the main outlet of the Caia catchment.

Scenario	Prec.[mm]	Evapotr. [mm]	Streamflow [mm]
Actual	52.1	26.7	23.3
Future	47.9	31.4	15.4

The monthly streamflow time series provided by the SWAT simulations at the reservoir location were then used to run the optimization module and to obtain the indicators required to complete the analysis matrix for the mDSS. From the outputs of this module we extracted either environmental or economic parameters. In particular, as shown in Table 5 where we report the implemented analysis matrix, we obtained as environmental parameters the average (AvR) and variability (VaR) of the storage reservoir level, and as economic parameters the maximum irrigable area (Irr), the reservoir exploitation (RE, defined as the difference between the capacity and the average volume held in the reservoir), and the efficiency of the system (Eff, defined as the average value of the spillway flow during the surplus period). For the other socio-economic parameters such as the construction costs (TC, dam and connecting pipeline), the farmer risk income (FR), and the conflicts between users (CU), in the absence of a link between external data and the selected driving force, pressure, or state indicator, we adopted a "pairwise comparison" choice. In this phase of the work we have been supported by experts who expressed a relative judgment to describe the expected relative performance of the indicators under examination. This choice is made in accordance with a scale included in the mDSS, as proposed by Saaty (1980), ranging from 1/9 (extremely good) to 9 (extremely poor), and its robustness is quantified by a consistency index. The values achieved are given in Table 5.

Table 5. Analysis matrix (AM) for the actual scenario.

Parameters	Option 1	Option 2	Option 3
Irr	138	192	138.2
VaR	32.3	66.1	32.3
AvR	161.6	186.4	161.6
RE	30.3	65.5	90.3
Eff	5.9	3.9	5.9
TC	0.80	0.06	0.14
FR	0.15	0.69	0.16
CU	0.08	0.73	0.19

Table 6. Analysis matrix (AM) for the future scenario.

Parameters	Option 1	Option 2	Option 3
Irr	120	162	120
VaR	18.9	65.3	18.9
AvR	169.9	153.0	169.9
RE	22.0	138.9	82.0
Eff	1.7	0.0	1.7
TC	0.80	0.06	0.14
FR	0.15	0.69	0.16
CU	0.08	0.73	0.19

Once the decisional case in the current scenario (in our situation the initial scenario is that obtained referring to the observed dataset from 1960 to 1990) was defined in detail, we tested the alternative decisional options in a hypothetical situation different from the current one and deduced from the meteorological analysis previously described (we ran the SWAT model for a period representing 1990 to 2050). In particular, as already mentioned, we evaluated the water balance (Table 4, future scenario) for the whole catchment with a reduced precipitation and a new set of statistical parameters required to run the weather generator. We obtained, for a decrease in precipitation of around 10%, a corresponding increase in evapotranspiration of 15%. The combined impact on the outlet streamflow was to decrease it by 50%. In relation to these results and to the analysis conducted to generate the statistical parameters for the precipitation regime, we may infer that the change is in the direction of extreme events. We thus defined the future scenario, driven by climatic change, as one that is determined by events that are outside the decisional capabilities of the end-user and that could strongly affect hypothetical future water management measures. It is assumed that in such a future scenario only some of the selected indicators may change value under the effect of the hypothesized external drivers. In our case, as reported in Table 6, the changed indicators are those extracted from the output provided by the optimization module such as the irrigable area, the reservoir exploitation, the efficiency of the system, and the average and variability of the reservoir storage volume, while the other indicators remained unchanged. In particular, we found that the irrigable area, the average spillway flow (Eff), and the variability of reservoir level decrease for all three options. On the other hand for the average storage we found an improvement (increase) for the first and third options and a decline for the second one, whereas for the reservoir exploitation we obtained a decrease in value for the first and third options and an increase for the second.

The transformation of the indicators stored in the analysis matrix into evaluation indices for the evaluation matrix is a crucial step in which the decision maker judges the performance of the alternative options, as measured or estimated for the analysis matrix, in terms of preference with respect to the specific decisional case under examination. Of the three alternative procedures available in the mDSS for transforming the indicator values expressed in natural units into [0, 1] normalized evaluation indices, we used the standardised benefit and cost type (min-max and max-min normalization, respectively) procedures.

The last step in the implementation of the mDSS concerns the assignment of weights to the different criteria and the definition of the decision rule adopted to aggregate partial preferences and then rank the options. We assigned different weights to the three groups of metacriteria and, since the decisional problem has been configured as a water demand management problem, the group representing economic criteria was taken to be the most relevant (0.15), followed by the environmental (0.10) and the social (0.05) ones. For the decision rule we implemented the simple additive weighting (SAW). This decision method assumes additive aggregation of decision outcomes, which is controlled by weights expressing the importance of criteria. With the implementation of this rule we obtained as the best option the two dams interconnected (Option 2) with a score of 0.81. The actual single dam option (1) resulted as the second best with a score of 0.25, whereas the two dams disconnected option (3) scored 0.23. These results thus demonstrate how the actual water management situation of the Caia catchment could be improved by the construction of a new smaller dam and by its connection via pipeline to the current dam. Furthermore, this decisional option turns out to be the best one for the future reduced precipitation scenario as well.

Once the best option was established, we were interested in knowing how robust this choice was. To this aim a sensitivity analysis was carried out using the two approaches included in the mDSS, and it was found that in order to change the options' ranking (in particular option 1 against option 2), the weights have to be altered assigning more importance to environmental metacriteria, with more attention paid to the variability of the reservoir storage level.

5. CONCLUSIONS

We have investigated the performance of a hydrological model and a decision support tool in a decisional context, focusing primarily on water quantity issues related to different management strategies pertaining to the construction and connection of a new dam. The conjunctive use of these tools necessitates a formalization and description of the problem to be addressed, enabling evaluation of alternative and clearly defined options under actual and future climatic scenarios. This approach has shown its potenentiality in addressing multi-disciplinary and complex problems.

The structuring phase of the decisional problem (metacriteria definition, model simulations, and assignmet of relative criteria weights) has, however, brought out how the process is strongly affected by data quality and data availability. In particular, the collection of more detailed spatio-temporal observations related to the physical description of the problem needs to be adequately coupled with socio-economic information extracted from specific studies.

The application of a complex spatio-temporal distributed model such as SWAT with tools that have no spatio-temporal support such as the mDSS (and decision support systems in general) was facilitated in this study by the intermediary of an external optimization module to refine the post-processing of model outputs in order to achieve a closer interaction between the two systems. This link has underlined the necessity to use or develop more simple but physically realistic models able to provide inputs, representing the hydrological regime, to the decision making process.

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