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A Decision Support System for Optimal Use of Irrigation Water and Crop Selection

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Abstract. We propose a Decision Support System (DSS) for optimal cropping patterns and irrigation water management. The development of the DSS has three objectives. The first is to use mathematical models in order to optimize cropping decisions and irrigation policies under shortage of water in the Kingdom of Saudi Arabia. The second is to help growers exploit optimally their lands in places suffering from water scarcity. The third is to provide authorities with decision tools for water pricing and allocation. The optimization models are designed to determine which ones among competing crops to select for a given season/year, and how much land and irrigation water to allocate to each selected crop. In particular, some crops may be deliberately under irrigated to save water and hence to maximize the total area to be irrigated. The computer package estimates the expected yield of each of the competing crops in each irrigation level to be considered. Then, it implements the optimization models to provide the optimal cropping decisions as well as the corresponding irrigation policies. While the package is very sophisticated, its implementation is very simple and practical.

Introduction

While water resources represent a crucial factor in most economic activities (agriculture, industry, tourism, etc.), the Kingdom of Saudi Arabia suffers from water scarcity both in quantity and quality. This led the Kingdom to carry out huge investments to increase water supply through non-conventional means such as water desalination, which has been so far considerably costly. Therefore, it is very important that water consumers make the most efficient use of it by avoiding its wastage and by allocating it to the most profitable activities.

Cropping patterns and irrigation planning are the aspects of water management that constitute the focus of this paper. The problem can be described as follows:

At the beginning of each year/season, growers are confronted with a very complex decision problem concerning the choice of crops to be developed under the limited supply of water in order to generate the highest profit. Key questions for their cropping decisions include:

1. How much land to allocate to each selected crop?
2. Where to grow selected crops to make the best use of the initial soil conditions? This would allow, for instance, for crop rotation.
3. What fraction of the irrigation demand to satisfy for each selected crop at each irrigation stage? In other words, what would be the best tradeoff between under irrigating crops and extending the irrigated area?
4. What is the best allocation of irrigation water over the different development stages of a given selected crop in case of water deficit?

Also, it is very important for authorities to have tools to assess the value of water in agriculture. This would help in strategic decision making such as pricing water in accordance to its true value and to the costs incurred to mobilize it. An appropriate pricing would push users to save water and optimize its consumption. The value of irrigation water would also help authorities in reallocating water most efficiently among competing regions and even competing sectors. In this paper, we develop an optimization-based DSS to help growers deal efficiently the questions raised above.

Literature Review

Yeh (1985) presented a review of the state-of-the-art of mathematical model developed for reservoir management and operations up to the year 1982. The optimization models surveyed include deterministic and stochastic linear programs, deterministic and stochastic dynamic programs, nonlinear program, simulation, and their combinations. In the following, a survey of the OR applications in the agriculture economics and water reservoir management published after 1982 is presented by the type of mathematical optimization models used.

Linear programming has been one of the most widely used mathematical optimization models in agricultural resources management. Qingzhen *et al*. (1991) described an interesting project related to the development of optimal production plan for crops and livestock in Chang Qing County (China). In the course of the project, the authors developed four large-scale linear programming models for different weather conditions and combinations of crops and livestock production. According to the authors, the implementation of the optimal production plan resulted in an increase of 12.33% in the net profit from crops and 53.77% in the livestock production.

Duffuaa (1991) developed a chance-constrained model for the operation of the Aswan High dam in Egypt. The goal of the model was to determine the optimal allocation of water that minimizes the total benefits through its return form agriculture and hydroelectric power. Agriculture requirements such as the minimum amount of water allocated for irrigation purpose are among the constraints of the model. The author also assumed that the demand for water is known over a certain horizon. Using the zero order decision, the author transformed the problem to a deterministic linear program that he solved using the LINDO package.

Azaiez and Hariga (2001) developed a single period model for the conjunctive use of ground and surface water in a multi-reservoir system, where withdrawals from aquifer are established only under emergency cases. The inflow to the main reservoir and the demand of irrigation water at local areas are considered stochastic. The model adopts deficit irrigation and attempts to maximize expected total profit for the entire region using convex programming. This model has been extended to a multi-period model and has been approached using chance-constrained programming (Azaiez *et al.*, 2005). Haouari and Azaiez (2001) proposed a multi-stage linear programming model for optimal cropping patterns under water deficit in dry regions. The model identifies both the total area and the irrigation level allocated to a given selected crop taking into account the possible successors and predecessors of this crop.

The Decision Support System

The DSS configuration is represented by the flow chart in the Appendix. A database is developed and contains data related to the candidate crops, the climate information, and the soil information at the region of interest. The database will interface with several models to feed the master optimization module, which will derive the optimal cropping and irrigation policies. These intermediate models are the water-yield model, the optimal irrigation model, the risk model, the season model, and the single crop model. The outputs of some of these models will be direct inputs to the master optimization model. Moreover, some of these models may interface before generating some other inputs to the master optimization model. A brief description of each of these models and their roles will be introduced.

Water-yield model

This model develops a relationship between the applied irrigation water and the corresponding expected yield for each given crop. In particular, the model estimates full water requirement of a crop over each growth stage that provides the maximum yield. This maximum yield is also estimated by the model. The estimation procedure is made first to a reference crop (usually alfalfa or grass). Then, it is adapted to the remaining crops as given in Doorenbos and Kassam (1979). When deficit irrigation is applied, then the model estimates the decrease in yield over each growth stage of the crop using the yield response factor of the crop at the given stage. The calculations actually provide the ratio of actual to maximum yield in terms of the yield response factor and the ratio of actual to maximum evapo-transpiration that occur respectively when deficit irrigation and full irrigation requirement are applied. A large number of input parameters are used in the assessment procedure. These include climate, geographic, soil, water and crop parameters. The flow of equations needed in the calculations procedure are coded using visual basic. The different inputs used are mostly default values stored in the database. These values are subject to modifications and updating by the user through user interface before the required calculations are performed.

Optimal irrigation model

This model determines in case of applying deficit irrigation the optimal water allocation over the different growth stages to make the best use of the different sensitivities of crop yield to water stress at the different growth stages in order to maximize expected crop yield. These sensitivities are estimated through the yield response factors of a crop over each growth period. The suggested policies are so that relatively insensitive periods (with low values of the yield response factors) receive low shares of irrigation water and vice versa. A dynamic programming formulation is proposed. This formulation is adapted to the most commonly used formulae of actual yield as a function of applied water.

The risk model

This model assesses the user risk aversion coefficient. It provides a simple decision problem with risky outcomes. The question addresses preferences over risky returns (50-50 chances of making good returns vs. having nothing) against sure returns but with lower values than the expected returns of the risky choices. Alternative answers are displayed to the user reflecting different risk attitudes. The selected answer will be used by the model to assign a pre-specified risk-aversion coefficient (RAC). This risk-aversion coefficient will be used in the objective function of the master optimization model by penalizing risky cropping policies proportionally to the estimated value of RAC. Consequently, users with relatively high values of RAC (corresponding to highly risk-averse decision-makers) are expected to obtain non-risky cropping policies at optimal exploitation.

The season model

Water supply is naturally seasonal. Moreover, it is usually at its peak when demand is low (during wet periods) and vice versa. Further, the same growth period of a given crop may fall in two distinct irrigation seasons leading to different abilities to satisfy some selected irrigation level for that period. Consequently, it is important to account for the seasonal supply when allocating water to crops overtime. This model uses the season and crop information in order to determine how growth periods lie with respect to the different irrigation seasons. This helps selecting feasible irrigation levels for the same growth stage that lies in more than one season. A simple algorithm is developed for that purpose.

The single crop model

This model attempts to determine for a given crop the best tradeoff between land use and irrigation level. The idea is to find out to what level it is profitable to expand the irrigated area at the expense of reducing the irrigation water to apply per ha when the volume of water available is not enough to satisfy full water demand and use the total available area. The model considers both cases of limited and unlimited land. The model determines the possible irrigation levels and the associated water volume for each growth stage of a given crop. It also performs several calculations needed in identifying some of the constraints parameters both for this single crop model and for the master optimization model (e.g., maximum land that can be used, maximum irrigation level that can be applied, how feasible to grow two crops in a row accounting for their life seasons, etc.). It interfaces with the optimal irrigation (dynamic programming) model, the season model and the water-yield model to perform the required calculations. It also feeds the master optimization model with some inputs. The model is a combined LP-DP optimization model.

The Master Optimization Model

Overview of the model

The model considers multiple crops competing for both land and irrigation water. The question the model attempts to answer is: what is the best allocation of land and water, both in time and space, among crops in order to maximize the net profit of a given farmer/agricultural company? Water allocation, in this case, should be directed towards increasing the yield of the most profitable crops. Therefore, low-value crops will have comparatively low shares of water and land and high-value crops will have the high shares.

This model tries to determine the optimal cropping pattern of the land of interest for a given year. Each selected crop must be grown according to its cropping period. Therefore, some crops may not be following others in the cropping plan because of overlaps in their cropping periods. Moreover, some crops are considered as good successors/predecessors of other crops if not only when it is feasible to crop them consecutively (in the right order), but also it is productive to have them cropped in a row.

Maximizing profit depends in part on the market conditions. For some farmers, some crops can not be totally marketed if the production exceeds some particular level. This suggests setting in the model an upper bound for the maximum quantity to be produced. Similarly, some minimum amounts of some crops may be dictated by contractual commitments with retail companies. This may be the case even if those crops where not considered as high profit crops.

The model accounts for the market requirements while searching for an optimal policy. The model also considers the seasonality in water availability. It is assumed that the year consists of four different irrigation seasons, each with a certain pumping capacity. Total water allocation for all selected crops in a given season can not exceed the pumping capacity of each irrigation season. Moreover, the model accounts for the irrigation efficiency of irrigation systems used in different pieces of land. In addition, the model considers the fact that part of the land might be still occupied by some crops at the start of executing the cropping plan but would be made available later and could be used by some successors. That is, the model keeps track of land availability and growing crops overtime.

Technical details about all the models above are given in Al-Harkan *et al*. (2005).

Model objective

The model objective is to maximize the weighted profit (accounting for risk) of land exploitation by determining the following:

- The area of land to be allocated to each selected crop.
- The best sequence of the crops to be grown over the same land accounting for crop rotation.
- The irrigation level to be applied to each growth stage of the crop life of selected crops.
- The cumulative amount of water to be consumed by each selected crop.
- The expected yield of each selected crop according to the selected cropped area and the selected combination of irrigation levels.
- The expected profit of each selected crop.

Methodology

A mixed integer programming model is developed using various inputs (as explained in the Appendix). The model uses several sets of constraints, namely water and land availability constraints, market constraints, time constraints and mass balance constraints. Crop rotation is considered by introducing a penalty factor named "predecessor coefficient". The values of this factor vary between 0 and 1. This factor will multiply the expected perfect yield of the successor. In particular, low values of the predecessor coefficient indicate that the successor will suffer a great yield reduction if cropped after the given predecessor.

In addition, a binary variable is introduced in the model to control the time feasibility of selecting two crops to be grown in a row. This variable is of great importance in the optimization procedure as it significantly reduces the size of the problem by eliminating infeasible combinations of crops. The model receives the information regarding each candidate crop from the single crop model. Other information is also received as inputs (as explained later). The model is implemented using LNIGO 8.0 software to determine the optimal policy.

Model inputs

The inputs of the model can be categorized in three different categories:

1) Land inputs which cover:

- Current crops that are previously grown over the land of interest.

Also, for each of the current crops, the inputs cover:

- Cropped area.
- Current crop ending date (including the harvesting duration).
- Irrigation system efficiency.

2) Irrigation season inputs:

- Available amount of water for each irrigation season.

3) Candidate crops inputs:

- Earliest cropping date.
- Latest cropping date.
- Growth period in days.
- Harvesting period in days.
- Selling price per ton (maximum, minimum, and average).
- Cost per hectare (maximum, minimum, and average).
- Market constraints (minimum and maximum requirements).

All these inputs are to be entered by the user. The database, however, contains some default values. The remaining inputs are as follows:

- The most promising combinations of the different irrigation levels for each growth stage of the crop life (say the best 20 combinations of levels. These are taken from the single crop model discussed above. Moreover, the number of promising levels is adjustable).
- Water consumption in each season associated with each combination of the irrigation levels for the crop growth stages (obtained from the single-crop model and could be modified by the user).
- Expected yield associated with each

combination (obtained from the single-crop model and could be modified by the user).

- Predecessor coefficients (default values in database which are set arbitrarily but reflecting the adequacy of crop successions).
- Binary variable called Possible that takes the value one if the predecessor coefficient is positive (from the single-crop model).

Model outputs

The outputs are categorized into two categories:

General outputs

- Total water to be consumed in each irrigation season.
- Total expected yield.
- Total expected profit.

Detailed outputs

For each selected crop, the model will determine:

- Allocated area.
- Immediate predecessor.
- Specific piece of land (identified by the existing crops at the start of the cropping plan).
- Cropping date.
- End of growth date.
- End of harvesting date.
- Water to be consumed.
- Selected irrigation level for each growth period.

The DSS will display these outputs through five reports; namely, general report, detailed crop report, water allocation report, land exploitation report, and irrigation season report.

System Evaluation by Practitioners

During field visits by the authors to Al-Jouf region (north of KSA), an evaluation form has been submitted to several local managers of different departments at NADEC Co. and at Al-Jouf Co., posterior to a presentation of the system and some implementations based on the company's own data. Ten responses have been obtained. Most of the managers were very satisfied with the DSS. In particular, they find the system very appropriate in addressing their real planning problems. Moreover, they were impressed by the system ability to solve complex situations with many conflicting factors, its high flexibility to adapt to different contexts, and the ease to manipulate it. Overall, they find the DSS as a valuable aid to their cropping and irrigation plans.

Concluding Remarks

In this study, a decision support system (DSS) has been developed in order to help agriculture companies make the optimal water and land exploitation for a given year. The DSS suggests the best crop mix accounting in particular for the profitability of each candidate crop, land and water availability, crop growing seasons, crop rotation, and marketing constraints. The DSS determines specifically the crops to be selected, the land to be used for each selected crop, the crop predecessors and successors, water use overtime, the level of deficit irrigation if any, and the expected profit out of each crop and for the entire exploitation.

The DSS uses several mathematical models to estimate water requirements, crop yield at different irrigation levels, water availability at different irrigation seasons, feasible sequences of successive crops, profit, best tradeoffs between land use and irrigation levels, risk behavior of the user, and daily irrigation levels needed to satisfy the overall irrigation policy. Masses of inputs are used. They are stored in the database, calculated by the DSS models, or entered by the user. The output of the DSS is configured in several reports specifying the main exploitation policy and the details needed to implement it.

The DSS is highly flexible and could adapt to different contexts. Its inputs could be continuously updated. It could, therefore, fit all users and all regions of the Kingdom provided that the required data is available. It offers also the opportunity for the user to plan his exploitation for several years to come and to benefit the best from crop rotation over long periods.

The DSS is a user friendly package and does not require much training to be efficiently operated by non-sophisticated users. Its options and screens are considered of professional quality as witnessed by the several highly ranked personnel of the companies to whom the DSS was exposed. The DSS in its present form was also considered as a valuable tool for solving companies' problems of water use, farm exploitations and future plan preparations.

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Appendix

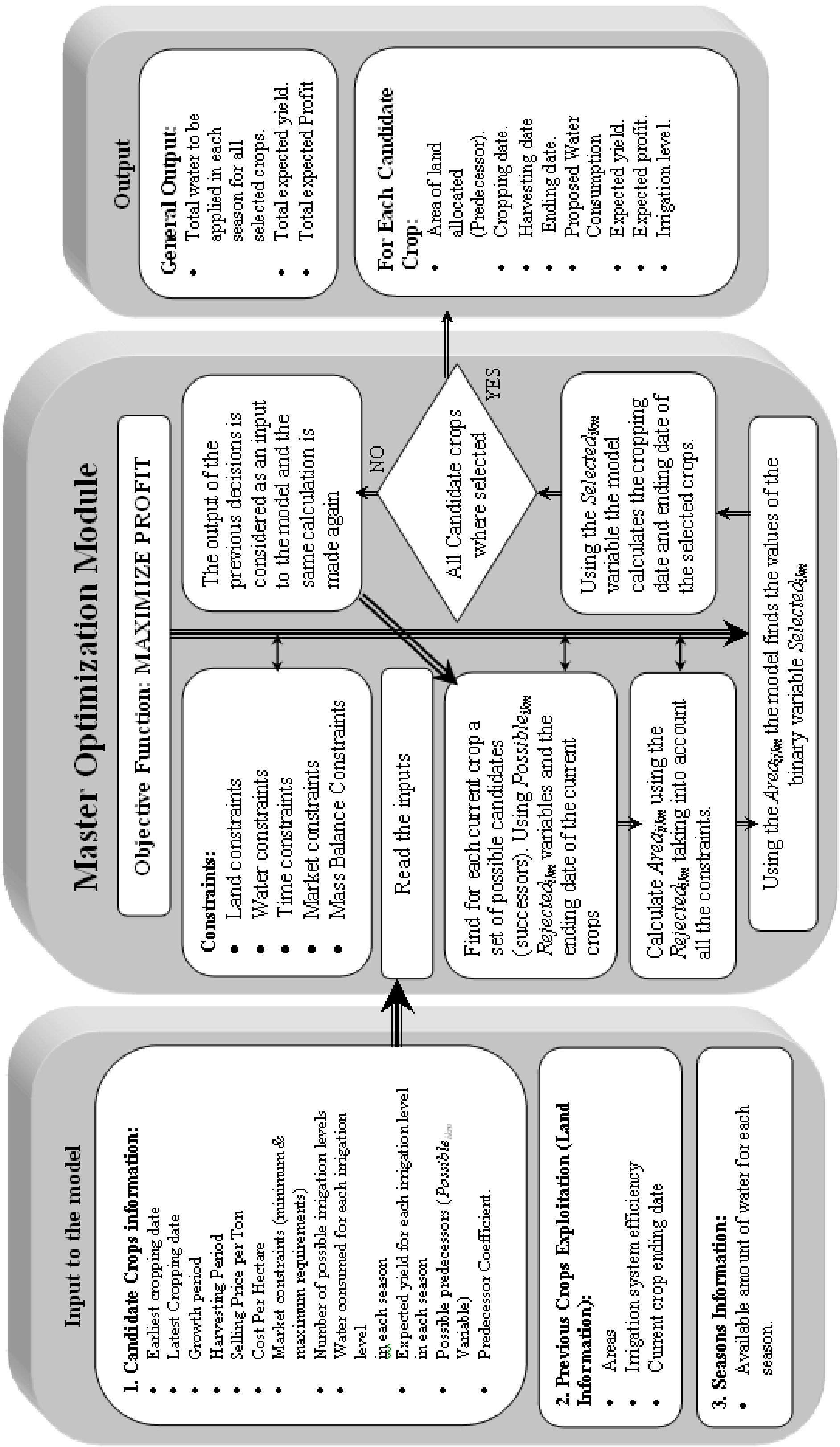

Fig. 1. The master optimization flow chart.

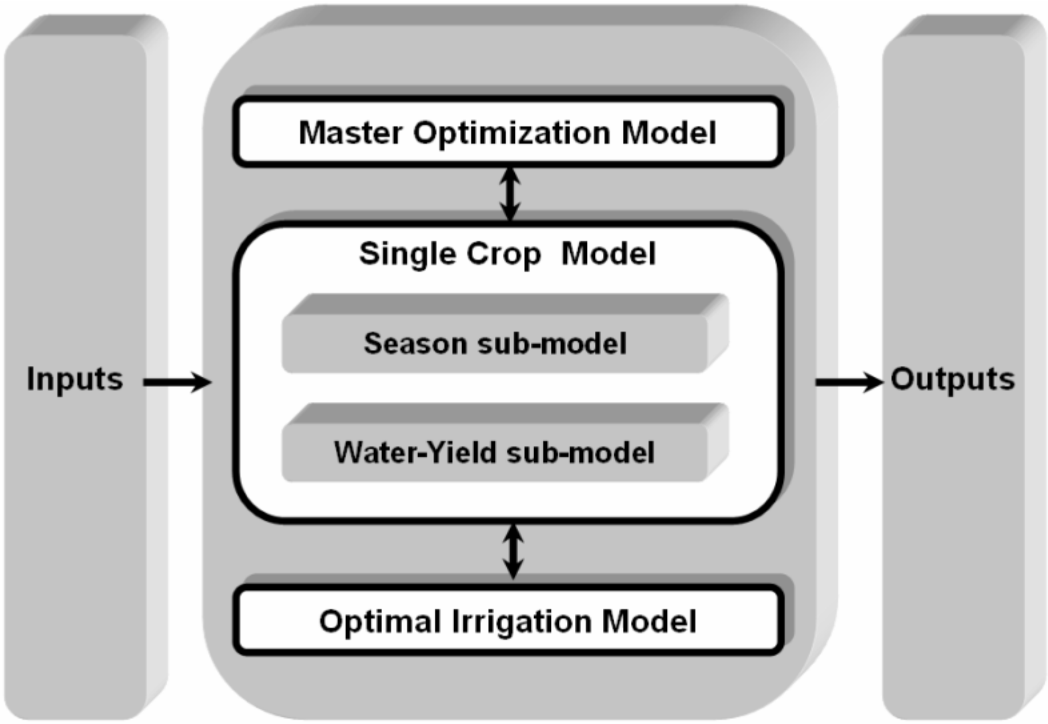

Fig. 2. A brief representation of the information flow among the different models.

تطوير نظام القرار ا ساند للاستعمال الأمثل ياه الري واختيار ا اصيل

إبراهيم بن مد ا ركان، و مد ناصر عزيز،
ومنصر عبدا ميد حريفة، وعبدالر ن بن علي العذبة

قسم الهندسة الصناعية، كلية الهندسة، جامعة الملك سعود،
ص ب ٨٠٠ الرياض ١١٤٢١، المملكة العربية السعودية

مد بن عبدالر ن الفوزان

مدينة الملك عبدالعزيز للعلوم والتقنية، الرياض، المملكة العربية السعودية

(قدم للنشر في١١/٠٤/٢٠٠٧م؛ وقبل للنشر في ٠٦/١١/٢٠٠٧م)

الكلمات ا فتاحية: البرمجة الخطية، البرمجة الديناميكية، نظام اتخاذ القرار، إدارة مياه الري، اختيار المحاصيل الأمثل.

ملخص البحث. يحتوي هذا المشروع على ثلاثة أهداف. يتمثل الهدف الأول في تطوير نماذج رياضية لبلوغ أفضل القرارات الخاصة باختيار المحاصيل الزراعية وسياسات الري في ظل شحة الموارد المائية بالمملكة، أما الهدف الثاني فهو يعنى بدمج السياسات الزراعية والمائية المثلى ضمن نظام مساند للقرار يكون مرنًا وسهل الاستخدام لمساعدة المزارعين على حسن استغلال أراضيهم ومواردهم المائية عبر تنفيذ تلك السياسات المثلى، كل حسب واقعه، في حين يخص الهدف الثالث توفير أدوات علمية لصنع القرار يساعد المسؤولين على السياسات المائية في المملكة على تسعير وتوزيع المياه بشكل أمثل.

تقوم الحزمة البرمجية، والتي وقع تطويرها أثناء المشروع، بتقييم متوقع الإنتاج لكل محصول مرشح للاختيار ضمن السياسة الزراعية ولكل مستوى من مستويات الري الممكنة، اعتبارًا إلى عوامل عدة تشمل خصائص التربة والمناخ وجودة المياه وقابلية المحصول للري الناقص والجدوى الاقتصادية وعنصر المجازفة. بعدها، تحدد نماذج المفاضلة السياسة الزراعية المثلى مع تفاصيل استغلال الأرض وطرق توزيع المياه بشكل ديناميكي، آخذة بعين الاعتبار خيارات المستخدم وتعامله مع عنصر المجازفة. ويتمتع النظام المساند للقرار بمرونة عالية تسمح للمستخدم إعادة النظر في بعض الاختيارات أو تعديل بعض البيانات حسب المستجدات أو تحليل عدد من السيناريوهات التي تساعده على تحديد الخطط المستقبلية.

يعتقد أن تكون مخرجات المشروع ذات فوائد هامة للمزارعين لمساعدتهم على اتخاذ القرار بشكل علمي مما يكفل لهم استخدام أراضيهم بأعلى جدوى اقتصادية مع ضمان ترشيد استخدام مياه الري، كما أن القيمة الهامشية للمياه أثناء الاستغلال الأمثل تساعد صناع القرار على الحصول على أدوات كمية ذات صلة بتسعيروتوزيع مياه الري مما يعين على اتخاذ قرارات فاعلة ذات بعد إستراتيجي تخص السياسات المائية بالمملكة.