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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

ROBUST PLANNING OF IRRIGATION CONSIDERING WATER CONSUMPTION AND REVENUE *

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ABSTRACT

Water scarcity is a problem for many regions which requires immediate action, and solutions cannot be postponed for a long time. It is known that farming consumes a significant portion of usable water. In this study, a decision support model of bi-objective stochastic linear formulation is proposed. The model is generating annual planting plans together with water consumption projections for each farmer in the region while taking revenue of the overall harvest into account. The structure of the proposed model maintains robustness against the volatilities in precipitation, yield, and market price. The inherent trade-off between water consumption and revenue lends itself to multi-objective planning. This is a perspective especially useful for regional administrations to plan next year's crop pattern together with agricultural incomes and irrigation expenses. Furthermore, it is also shown how the model can be used to investigate the potential of rainwater harvesting or switching to water-efficient irrigation methodologies. The decision support model is especially unique in the sense that it can generate a set of Pareto optimum solutions as opposed to a single objective counterpart. This property is helpful in terms of not only providing a broader perspective to evaluate and project the possibilities but also increasing the applicability of the results by providing flexible design framework

Keywords: *Irrigation, crop planning, rain harvesting, decision support, robust optimization.*

Özgü TURGUT

SU TÜKETİMİ VE KAZANÇ ODAKLI, DİRENÇLİ (GÜRBÜZ) SULAMA PLANLAMASI

ÖZ

Su kıtlığı birçok bölgede ertelemeye göz yumulamayacak ölçüde acil çözümler bekleyen bir problem haline gelmiştir. Tarımın kullanılabilir su kaynaklarının ise önemli bir kısmını tükettiği bilinen bir gerçektir. Bu çalışmada bu gözlemlerden yola çıkılarak, çift amaçlı, doğrusal ve stokastik bir karar destek modeli sunulmuştur. Söz konusu model seçilen bölgede yıllık ekim planı ile birlikte yıl boyu gerçekleşecek su tüketim tahminlerini, yılsonu hasatına ait muhtemel kazancı göz önünde bulundurarak çıktı olarak vermektedir. Modelin dirençli(gürbüz) yapısı tüm bu çıktıyı üretirken yağış, verim ve ürünlerin ortalama birim fiyatlarındaki belirsizliği hesaba katmasından kaynaklanmaktadır. Çift amaçlı yapı ise su tüketimi ve kazanç arasında varolan çelişkinin doğal bir sonucudur. Sunulan modelin bakış açısı genel olarak yıllık ekim planlaması ve su dağıtımı gibi hizmetleri yürütmeden, ayrıca yıllık tarım gelirlerinin öngörülmesinden sorumlu idari birimlerle örtüşmektedir. İlaveten, çalışmada yağmur hasatı ve yağmur sulama sistemleri gibi iki önemli teknolojinin potansiyel katkısı da örnek alan çalışması üzerinde gösterilmiştir. Bu noktada, modelin çift amaçlı yapısından kaynaklanan avantajlarının bir kez daha altı çizilmiştir. Zira, tek amaçlı benzerlerine kıyasla bu yapıdaki modeller, birden fazla optimum plan çıkarabildiği için uygulayıcıya karar alma noktasında daha geniş bir perspektif ve esneklik sunmaktadır.

Anahtar Kelimeler: *Karar destek ünitesi, eniyileme, sulama, yağmur hasatı, tarım planlama..*

1. INTRODUCTION

Water is one of the major resources of life on Earth. Nonetheless it is not an exception in the list of values at risk due to the unsustainable consumption policies. Agriculture is the biggest consumer of freshwater in the world, amounting to up to 70% of the total use [FAO 2016]. Accordingly, several measures are being developed around the World to impede uncontrollable depletion of water resources. The United Nations (UN) reinforces water's place as a fundamental human right. To reduce the pressures on the hydrological system, the Secretary-General highlighted key game-changers such as reducing the unsustainable use of water in food production and agriculture while designing and implementing a new global water information system to guide plans and priorities by 2030. The measure relies on the fact that agriculture can be made more efficient using alternative water sources, low water crops, saline tolerable crops and practices to reduce erosion. In rural areas, water scarcity caused by agriculture, which increases global freshwater withdrawals, was spotlighted by many stakeholders as a challenge. Effective policies pay off as it has been underlined in the same report "Solidaridad Network in Asia has extensively worked in Agri-water space, which has resulted in saving of about 500 billion liters of water savings in the last 8 years.

On a national scale the responsibility of government on monitoring, recording and reporting of major water resources has been guaranteed with some regulations[1]. Accordingly, Forest and Water Ministry has a role for managing use of these resources efficiently. The National Administrative Water Agency (AWA) is the main institution that takes the major responsibility in this respect. Figure 1 summarizes the decision-order mechanism of administration together with where the proposed tool is plugging into this system.

Alternative sources for irrigation are under development. Using recycled water is one of the methods that aims to reduce demand for clean water. However, farmers still express concern about using recycled water [McOmber et al. 2021] ; and their willingness to use recycled water is prone to incentives [Cultice et al. 2016]. Rainwater harvesting (RWH) systems offer a practical way to mitigate water stress. RWH systems provide direct runoff containment while simultaneously storing water, which can then be used for irrigation [Jin et al. 2023]. Rainwater harvesting takes attention by individual buildings from the roof top or gardens for individual use. A recent study by Quintana-Ashwell et al. [Quintana-Ashwell et al. 2022] showed how

[1] https://www.resmigazete.gov.tr/eskiler/2017/02/20170216-1.htm: Orman ve Su İşleri Bakanlığından: SULAMA SİSTEMLERİNDE SU KULLANIMININ KONTROLÜ VE SU KAYIPLARININ AZALTILMASINA İLİŞKİN YÖNETMELİK 2017 Sayı : 29981

much can be gained by efficient irrigation through on-farm storage systems from the techno economical perspective. In addition, “road rainwater harvesting” appears as an alternative as another possible way of harvesting rainwater [Molle et al. 2018]. The negative aspects of rainfall can be reversed if roads are systematically used as instruments for rainwater harvesting [Nissen-Petersen E. 2006]. Thus, road harvesting can generate substantial positive impacts: more secure water supply, better soil moisture, reduced erosion and respite from harmful damage [Demenge et al. 2015].

Figure 1. *Role of the proposed decision support model in national agriculture and water resource management*

The World Bank initiated a project (SUTEM[2]) together with AWA piloting in 4 different zones. The project aims to extend the modernization beyond the watering centers of AWA utilizing IT technologies while collecting all the information

[2] https://dsi.gov.tr/Sayfa/Detay/725

gathered from water consumers centrally. The database will eventually contain data coming from various watering options as well as physical condition of the watering sources, socioeconomic conditions of the users (number of farmers, their planted area, crop types). Providing reliable and central flow of these types of data is going to establish the required infrastructure for analytical decision support systems while managing the scarce and valuable water resources. Researchers and innovators are making this monitoring and control possible by proposing cost effective sensor technologies [Garcia et al. 2020; Bwambale et al. 2022]. A representative list for these technologies might contain leaf water stress monitoring sensor [Daskalakis et al. 2018], a multi-level soil moisture sensor comprised of copper rings placed along a PVC pipe [Guruprasadh et al. 2017], a water salinity monitoring sensor made with copper coils [Parra et al. 2013] or a water turbidity sensor made with colored and infrared led emitters and receptors [Sendra et al. 2013].

Irrigation requirements depend on weather conditions. The conditions can be classified as cool, normal and warm [Kodal et al. 1997]. An average irrigation requirement can be calculated representative for each of the corresponding weather conditions. In this study not only weather conditions but also crop type has been possible to be included into the total water requirement by relying on the outputs of a recent project by AWA [TAGEM 2017]. In addition to including the volatility in precipitation the model takes the stochasticity in yield as well based on the historical data. Input costs, changes in climatic conditions causes changes in yield loss due to pests, agricultural tools and machinery failure, theft, fire, crop damage due to excessive water, crop loss due to drought and lack of technical information were chosen as criteria [Melek Isik 2023].

The proposed model generates a yearly farming plan not only focusing on the total water consumption, but also total revenue generated by the overall production. However, market prices are highly volatile due to various external factors. It is not possible to claim realistic and applicable results without considering the financial aspects of farming.

One of the first examples of a decision support model that is built to serve similar purpose belongs to Aglamis et al. [1997]. The aim of this study was to support Murted Irrigation project through a linear program in order to determine the crop pattern in the region in addition to using the tool of FAO called DASI at that time for economic analysis. The irrigation schedules were generated with an external program called CROPWAT in this study [Aglamis et al. 1997; Beyribey et al. 1997]. In 2015 two separate studies are published in which robust planning perspective is adopted for water management in two different contexts [Dong et al. 2015, Yasari and Pishvaie 2015]. Both methods use genetic algorithms instead of deterministic models that guarantee optimality. In recent years with the aim of incorporating all the stochasticity, two stage stochastic programming has become a popular technique in generating decision support for planning irrigation water and connected crop pattern with applications in different parts of the World [Laureti et al. 2021; Li et al. 2019; Maqsood et al. 2005]. Moreover, after the first submission of this study two studies have been published from China in which multi-objective robust optimization approach is used in linear programs. The input-output structure (i.e. functionality) of the models differ from each other and this study from several aspects [Guo et al. 2023, Mahdi et al. 2023]. In this study, a mathematical model is proposed to support planning and decision-making process at the top level while prioritizing robustness, i.e. worst-case conditions of the solutions. Moreover, the model has a bi-objective structure which considers two conflicting objectives, namely total water consumption of the proposed crop pattern and total revenue that can be obtained from the resultant harvest. Accordingly, major volatilities which are scrutinized by the model are the ones that affect both objectives directly, listed as precipitation, yield and market price of the products.

The rest of the article proceeds with materials and methods where details for calculation of water requirement, mathematical model and stochastic scenario generation are presented. Then it is followed by results and discussions starting with the introduction of the case study. Finally, a summary of the results and benefits of the proposed tool are provided as well as possible future extensions and open research points.

2. MATERIAL AND METHODS

For various irrigation and sewer models, monitoring for drought and many other hydraulic systems effective water consumption (*EWc*) of the plant is a necessary input parameter. Therefore, the recent guideline prepared by TAGEM and AWA [TAGEM 2017] is used to derive the unit water requirements of each crop type. The *EWc* values for 85 different crop types are listed with respect to the region they are being planted in this document relying on data coming from 259 observation stations around the country. The utilization of the parameter for surface and other irrigation methods differ mainly as follows:

Net irrigation requirement (*dn*) is calculated directly including precipitation information (*Pe*).

$$dn = EWc - Pe \qquad (1)$$

In this equation Pe is assumed to be 80% of the average precipitation level of the month in the region. 80% is chosen as a common ratio to represent the effective precipitation level. *EWc* values are obtained from the guideline mentioned above for the selected region. The average monthly precipitation level of the focused region is obtained from the website of National Weather Office based on the observations between the years of 1991-2021.

For the rest of the irrigation techniques such as dripping or sprinkler the *EWc* is corrected as follows:

$$T = EWc * (Ps/0.85) \qquad (2)$$

Where *Ps* stands for the ratio of shaded area by the plant. This a percentage changes between 70-80 depending on the classification. The values used in the case study can be found in the Appendix. After making this correction the net requirement, i.e. *dn*, is calculated again based on eqn.1 which is followed by one last step that reflects the efficiency of the applied irrigation technique to the actual total irrigation requirement as follows:

$$dt = dn / (Ea*Ec) \quad (3)$$

In this equation Ea represents the irrigation efficiency which is assumed constant at 98%; and Ec represents the method specific application efficiency percentage. For the sprinkler method this parameter is assumed as 75% while it is 95% for dripping methods based on the same guideline.

2.1 Mathematical Model

The planning for the crop pattern can be managed with the help of following mathematical model. The uniqueness of the model stems from two separate properties. First the model considers several stochastic parameters in the context such as precipitation level, yield level and prices of the products in the market prioritizing the riskiest scenarios. The second peculiarity is due to the objective structure of the model. That is the model has a multi-objective structure, which considers the financial value of the products besides detailed water requirement of the farming plan of the region. All the notation for input parameters, decision variables and sets are presented with explanations under Appendix section at the end.

Based on the symbols, the following set of equations represent the constraints of the linear model where all the parameters are assumed as deterministic, i.e. has a constant value.

$$\sum_{f}^{F} dt_{c,s,p} \cdot X_{f,c,s} = WaterCons_{c,s,p} \ \forall s,c,p \quad (4)$$

$$\sum_{f,c}^{F,C} X_{f,c,s} \leq \ totalArea \ \forall s \quad (5)$$

$$\sum_{f}^{F} y_{c,s} \cdot p_{c,s} \cdot X_{f,c,s} = Revenue_{c,s} \ \forall s, c \qquad (6)$$

The model aims to reduce water consumption while trying not to sacrifice from the revenue. Therefore, the objective function contains both variables in a well-known multi-objective structure in the next section.

2.2 Robust Modelling for Stochastic Components

The stochastic parameters of the mathematical model belong to the precipitation, product yield and market price levels. To be prepared for volatility in any of these three factors, a robust modelling approach is adopted in this study. In stochastic programming the first step is to construct a scenario set. For that purpose, instead of assuming a single constant level, multiple values are chosen from the probability set (i.e. set of possible outcomes) of each stochastic factor. Each scenario in the final scenario set contains a different combination of these different levels as shown in Figure 2.

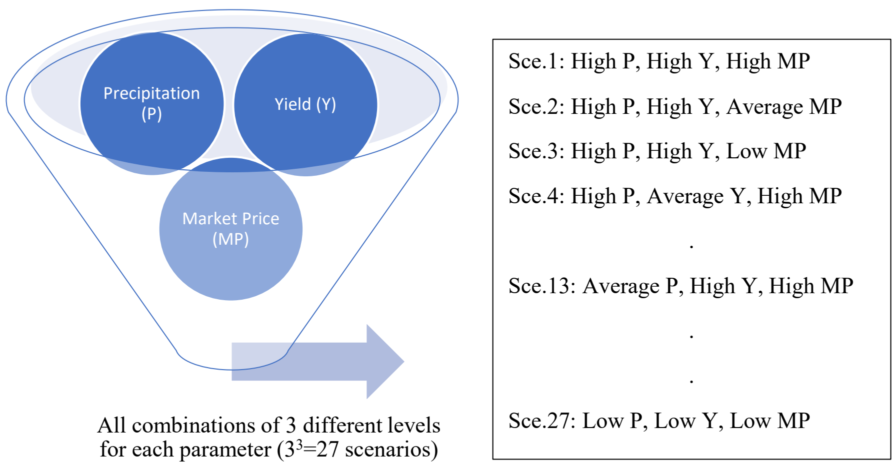

Figure 2. *Scenario generation process using three different levels of three stochastic parameters (precipitation, yield, market price)*

There are three stochastic inputs in this model as represented in Figure 3-5. First one is the average monthly precipitation level which is used to calculate unit water requirement coefficient, i.e. $dt_{c,s,p}$

The other ones are the yield for each crop type, $y_{c,s}$, and sales price, $p_{c,s}$, which are used to calculate the corresponding revenue for the planning period through multiplying with the resultant dedicated land, $X_{f,c,s}$, to each crop type. For each parameter three different levels are set based on its average value. The additional two levels to the average case scenarios are generated by specifying a lower and upper limit for each parameter as a percentage of its average value. The percentages are chosen arbitrarily in a way to create variety in the values but not generate unreal cases for the sake of variety. The percentages set to generate the lower and higher levels of each parameter are summarized in the following Figure 3-5.

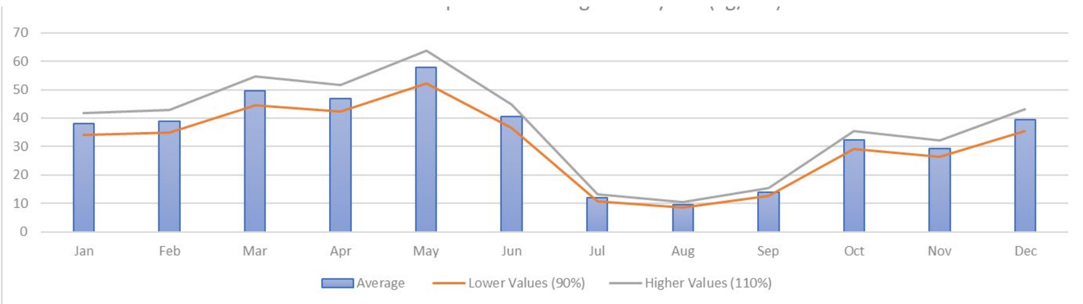

Figure 3. *Average, lower and higher bounds of precipitation (kg/m2) data per month for the crop set*

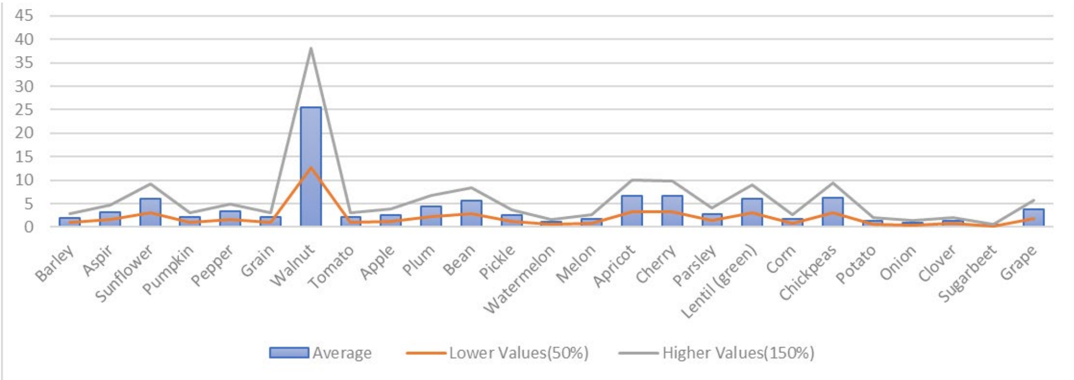

Figure 4. *Average, lower and higher bounds of market price (TL in 2021 values) for the crop set*

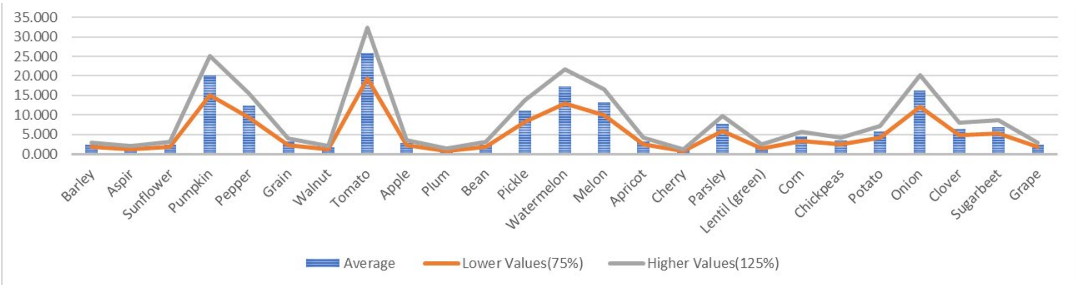

Figure 5. *Average, lower and higher bounds of yield values (kg/m2) for the crop set*

After forming 27 scenarios by assuming equal probability to the scenarios, some additional equations are necessary to insert robust decision-making attitude to the final plan. Main idea behind robust planning is obtaining the results that will keep you guarded against the worst scenario. Therefore, you need to watch the worst values of focused aspects. In our context we are interested in keeping total water consumption and revenue at a certain level as much as possible. Mathematically this goal can be expressed as a weighted sum of two deviations as follows:

Minimize {weight of water objective maximum deviation from target for total water consumption+ weight of revenue objective* maximum deviation from target for total revenue}* (7)

Same expression can be rewritten with concrete mathematical terms as follows:

There are two nonlinear terms in the above expression which stands for the maximum deviation from each target over all scenarios included. The nonlinear terms can be converted to linear form with the following additional equations. Also, a couple of auxiliary variables are added for the sake of neatness:

$$TargetWaterConsump - \sum_{c,p} WaterCons_{c,s,p} = SavedWater_s - ExtraNeed_s \quad \forall s \tag{8}$$

$$TargetReveue - \sum_c Revenue_{c,s} = BudgetDeficit_s - ExtraGain_s \quad \forall s \tag{9}$$

$$ExtraNeed_s \leq MaxExtraNeed \quad \forall s \tag{10}$$

$$BudgetDeficit_s \leq MaxBudgetDeficit \quad \forall s \tag{11}$$

Now the maximum deviations from the target values that we want to penalize are represented with $MaxExtraNeed_p$ and $MaxBudgetDeficit_s$. Therefore, the objective function can be formulated by representing the multi-objective point of view at the same time as follows:

$$\min\ [WeigthWater \cdot \sum_p MaxExtraNeed_p + WeightRevenue \cdot MaxBudgetDeficit] \tag{12}$$

The multi-objective structure allows to incorporate financial planning into the farm plan which will increase the applicability.

Based on this stochastic structure the robust model defined by equations (4)-(6) and (8)-(11) together with the objective function expressed by equation (12) identifies the optimum value of decision variables that generates minimum deviation from the target water consumption and revenue for the worst scenario. Besides, the results are expected to reflect the relative importance that is attributed to revenue and water aspects too.

The model is implemented with Gurobi C++ API and runs with Visual Studio 2022 of Windows 10 installation, on a machine of CPU model Intel(R) Core (TM) i7-4558U (@ 2.80GHz). Instances with approximately 50000 rows and 27025 columns are solved in around 1-2 seconds.

3. RESULTS AND DISCUSSION

There are three important parameters that can reflect major policy tuning measures about water management. Therefore, the baseline model is the version that contains the default values for these three parameters; namely *target water consumption and total revenue*, *shares of major irrigation techniques* used by the farmers and *weights* used in the objective function expression which represent the importance of water consumption and revenue relative to each other. The baseline results are followed by the insights obtained from the sensitivity runs where each of these factors in the sample region changed. The region selected for demonstration purpose (Figure 6) is the central Kayseri farming land whose territory is defined by the AWA observation station (station number 244) which is located exactly at 38,7178 N'' 35,4836 E''. Hence the EWc values that is used in calculating unit water requirement, i.e. $dt_{c,s,p}$, are drawn from the corresponding table in the guideline [TAGEM 2017]. In line with the guideline, the duration of each planning period is assumed as 10 days long. Hence the model horizon contains in total 36 periods. The baseline scenario relies on the self-capabilities of the AWA which mainly stem from the River Kizilirmak (Turkish Republic). Kizilirmak has a yearly average of 7 km^3 water capacity and goes through 11 cities. If all the cities have equal share the scoped region has a share of 7 km^3/11.

Figure 6. *Google map view of the focused region: Kayseri province (Turkish Republic)*

The details for approximating the capacity of Kizilirmak (Turkish Republic) in kg can be found in Table 1.

Table 1. *Kizilirmak is the major resource that AWA 's management responsibility. Hence the existing irrigation capacity is approximated with the up-to-date information of the river.*

Capacity Approximation for Existing AWA resources	Quantity	Units
Potential contribution of Kizilirmak	0.038	%
Annual flow of Kizilirmak	7	km3
Number of cities benefit from Kizilirmak	11	#
Ratio of the focused area in Kayseri (Turkish Republic) to the total farming area	0.33	%
Total water resource that can be used	7,980,000,000.00	kg

It is assumed that there are three main irrigation methods used in the region. The share of each method is broadcasted by AWA (2021) as follows: surface(wild) irrigation 60%, sprinkler 23%, dripping 17%. The robust stochastic formulation presented previously requires restrictions on the maximum total water consumption and minimum revenue generated to set targets and watch the maximum deviations from these targets. Both approaches recommended “cherry” as the best choice. The model identified two anchor points to recommend. Pareto 1 is the anchor, i.e. optimum plan, when revenue is prioritized with the weights; Pareto 2 is the recommendation that appeared as optimum when water consumption is prioritized.

It is observed from Figure 7 that the distance between two recommendations is similar for all scenarios. That is, planted area, revenue generated, and total water consumed of each Pareto are equally different as the result of best, worst and median values of the stochastic parameters, i.e. scenarios. For the median case revenue-oriented anchor recommends to plant 6566.69 ha cherry and it discerns to earn between 460.46- 2302.28 Mil TL (2021 values) depending on the scenario. Corresponding annual water consumption will change between 1927.47- 2335.29 (kTon). The water consumption-oriented anchor recommends planting 4925 ha cherry, and it projects to consume between 1445.61-1751.46 (kTon) annually. Accordingly, the revenue will reduce to a band between 345.34-1726.71 Mil. TL.

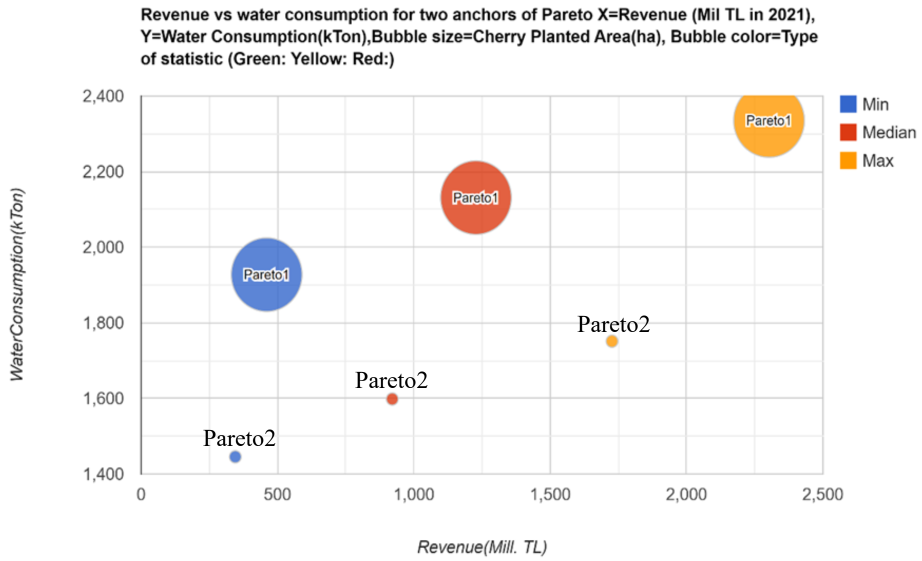

Figure 7. *Anchor results of water consumption vs revenue oriented stochastic models (both robust and multi horizon formulations generated the same results)*

3.1 Rainwater Harvesting

Using the proposed tool for changes on the water capacity is one of the functional actions to take. A possible reduction of the water flow of Kizilirmak can be modelled by simply reducing the target water consumption. In a similar manner, potential contributions to the available capacity can also be modelled easily. For demonstration purpose and generating sample results to promote investments in rain harvesting technologies the first sensitivity experiment is conducted for assessment of changes as the result of rainwater harvesting. There are two common approaches to harvest rainwater: roads and roofs. Instead of confining only to existing resources of AWA such as ground water and river basins, additional capacity can be created by investing in rainwater harvesting technologies on roads and/or roof tops. To demonstrate prospects of this sustainable approach the water consumption capacity is set to the potential estimate of the rainwater harvest of roads in the area. This potential can simply be calculated by projecting the area of available roads [Hari et al. 2018]. Depending on the type of road, water can be harvested with drainage system or roadside ponds. According to the statistics of the National Transportation Ministry [3], the city contains 1133 km long various types of roads. With an assumption of 5 m width the total area covered by the roads can be approximated as 1133*0.005= 5.665 km2. The scope area is one third of the total city area, then the total road area can be divided into three. Hence this can be used to make an approximation about the total amount of rainwater that can be harvested using the road harvesting technologies. In total if the required infrastructure can be set up (1133/3)*1000*5*Precipitation (period)[4] gives an estimate (kg) about how much water can be obtained from rain water harvesting monthly. At this point total rainfall (kg) per m2 in a month is assumed to be distributed evenly into three equal subperiods (i.e. same for each 10-day period). If the model is rerun by setting the target water consumption to represent sum of both dedicated capacity of Kizilirmak and estimated rainfall harvest, we obtain different results than the baseline. Recall that the objective function structure defined by the equation (12) is in multi-objective structure and has the ability to identify several Pareto results in between the anchors if there are any. The additional capacity provided by rainwater harvesting proved to have the potential to add variety to the recommended crop mix. The following results are obtained by weighing revenue and water consumption with changing the weight systematically.

Resulting 4 different Pareto solutions recommend a different crop mix. As can be observed from Figure 8, in terms of revenue Pareto 2-4 are identical. However, they

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[3] Kara Yolları Genel Müdürlüğü : IllereGoreDevletVeIlYollari
[4] https://mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=H&m=KAYSERI

vary from total water consumption point of view (Figure 9). Figure 10 shows in detail how crop pattern recommended by each solution differs.

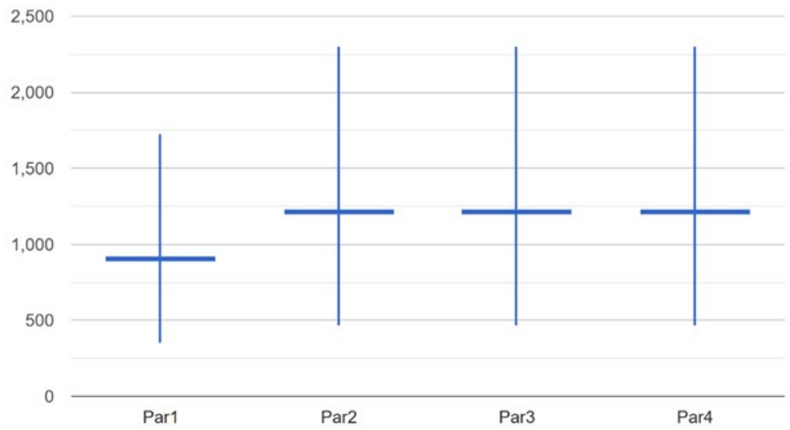

Figure 8. *Revenue ranges (Million TL in 2021 values) for 4 different Pareto recommendations*

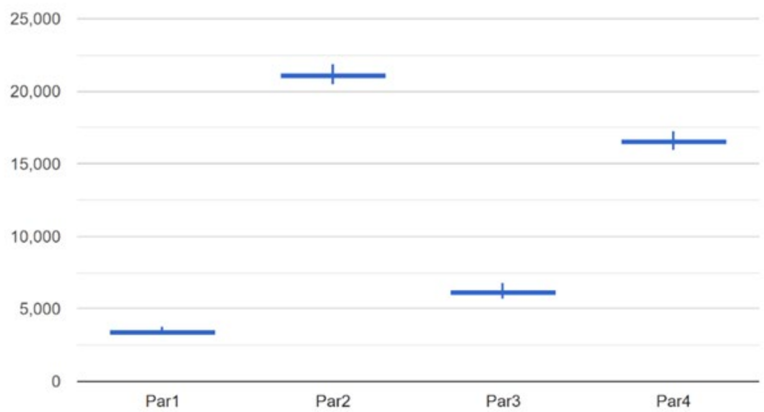

Figure 9. *Annual water consumption ranges (Million tons) for 4 different Pareto recommendations*

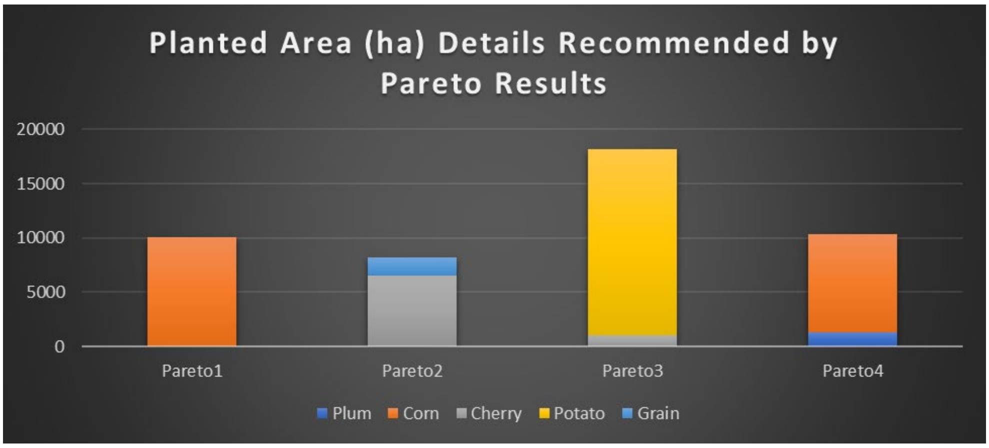

Figure 10. *Total area to be dedicated to the recommended crop mix*

Obtaining alternative Pareto solutions provides flexibility to the system managers in many aspects. That is, a decision maker can choose the final recommendation to be implemented by considering the current requirements of the decision-making moment relying on the flexibility provided by multiple alternative recommendations. Furthermore, it generates more insight into the possible outcomes of a system.

3.2 Transition to Efficient Irrigation Methods

It is indicated previously that the ratios for the type of irrigation used are based on the statistics provided by the AWA. In the last set of experiments, it is investigated how switching to dripping and sprinkler completely changes the optimal results. It should be emphasized once again that water efficient methods such as dripping, and sprinkler are preferred and implemented for frequently planted (at most 4 m apart) crops or tree gardens [FAO 2020]. The experiment scenario is developed based on this tendency, assuming wide farming crops are still using surface irrigation, however all other types made full transition to water efficient methods. The results are presented in Figure 11 and 12 for two Pareto solutions of the baseline, where resources are constrained to AWA's major resource.

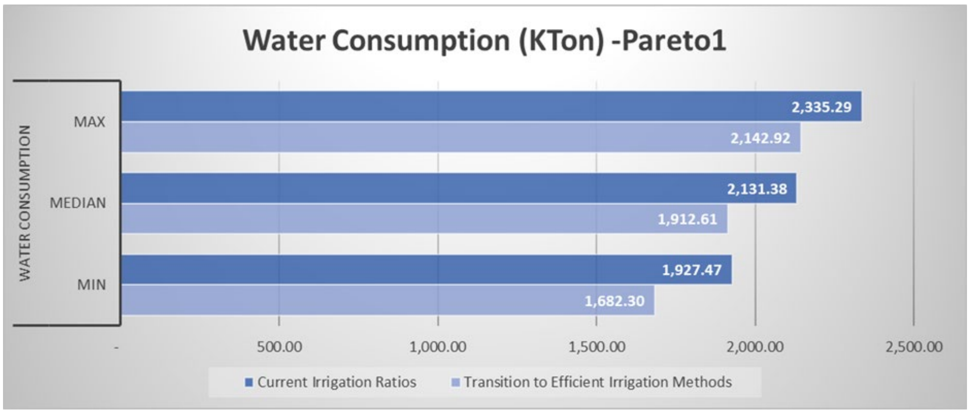

Figure 11. *Change of water consumption for the revenue-oriented anchor (Pareto 1) result when irrigation methods made a transition to dripping and sprinkler systems (keeping the current relative ratios)*

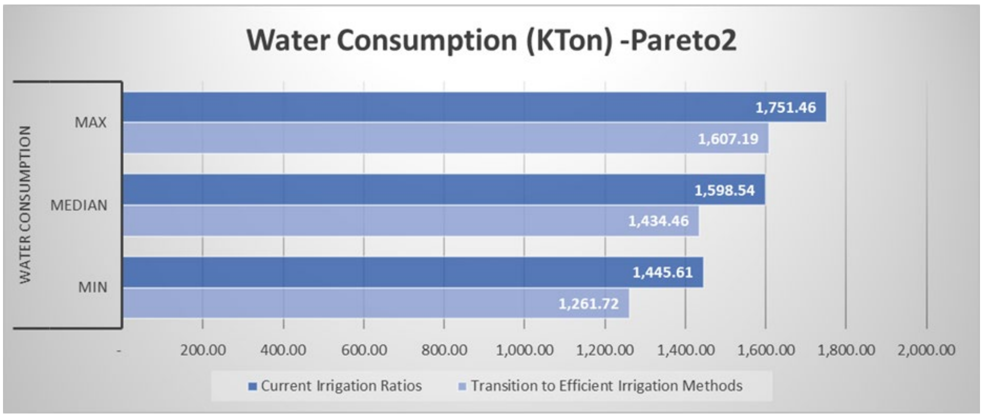

Figure 12. *Change of water consumption for the water consumption-oriented anchor (Pareto 2) result when irrigation methods made a transition to dripping and sprinkler systems (keeping the current relative ratios)*

The transition does not affect the final recommendation of the same crop type to the same amount of planting area. However, the resultant water consumption is being affected by around 200 kTon for all cases of both solutions.

4. CONCLUSION

In this study a robust stochastic optimization model is proposed as part of a decision support mechanism which is designed for use of regional water management authorities. The functionality of the proposed system and how it will fit into the existing water management administration is explained in Figure 1. The model takes water consumption and revenue targets which are set by the authorities and then generates a set of Pareto solutions, i.e. recommendations, by considering total water consumption and revenue obtained from the harvest at the end. The tool can serve both making projections during planning processes as well as generating the final plan depending on the valid policies.

In order to see the significant contribution of the tool a quick projection can be performed using the public data of 2022. The Ministry of Environment reported 44 billion m3 (42240000 kTon)[5] water spent on irrigation in the national scope. There is no actual water consumption data available per region. To proceed with a projection of better precision about the actual water usage of the region, we can use the last available (2022), demographics of TUIK: Kayseri hosts 1.69% of the total population. We can narrow it down further by considering the ratio of the scoped area to all farming land of the city from Table 1 (33%). Hence by multiplying the total water consumed by irrigation with these two ratios, the total irrigation amount of the selected region is estimated as 714014 kTon/yr. On the other hand, the proposed model does not project water consumption of more than 2500 kTon/yr even in the worst-case scenarios of the baseline tool. Recall the revenue target is set based on the actual prices (line 396) as 1152 Mill. TL. For most of the solutions this target is maintained while the possible revenue corresponding to the worst water usage scenario that is mentioned above, reaches 1500 Mill. TL.

Although in recent years the efforts making the transition to dripping or sprinkler watering systems instead of using surface watering started to pay off, it is also known that this transition is not necessarily translated into an increase in the capacity

[5] https://cevreselgostergeler.csb.gov.tr/su-kullanimi-i-85738

dedicated to other water consumption channels such as city water or power usage. To control and allocate the water resource more purposefully new watering systems has to be used with monitoring abilities that can limit the usage capacity for each farm. The proposed model is used to take advantage of rain harvesting on the final recommendations. It is observed that just by applying harvesting technology to 1% of the available roads in the area the variety of the crop pattern can be increased significantly. This observation is in line with the conclusions highlighted by Kovacs and Durand-Morat [2017] regarding the relationship between the increases in irrigation-intensive crops and groundwater need. Benefits of using additional potentials such as rainwater harvesting might become more obvious when the requirements of the other water consumers are integrated into the model with additional variables and constraints. Moreover, it is also shown how much switching to water efficient irrigation technologies can affect the total water consumption for the Pareto solutions.

In terms of extending the work from the methodological perspective two-stage stochastic programming can be re-considered-since there are already many studies that use this technique in literature as stated in the introduction. Two-stage programming is an intuitive choice of the modelers, because it requires two classes of variables representing the strategic and operational decisions, and indeed they automatically correspond to the annual planting and water consumption decisions respectively. When the worst-case stochastic scenario is not too different from the rest of the scenarios, robust formulation and the two-stage formulation will generate similar pareto set. However, for the cases where worst case scenarios are significantly different than the rest, which can also be interpreted as the case where there are significantly risky scenarios in the model, difference between robust modelling and multi-horizon two stage modelling can become clear. For such a study, the scenario generation process might be differentiated from the current work by utilizing the annual past data sets where such extreme combinations are observed instead of systematically varying the combinations within a given interval.

As another extension to the study a crucial aspect of decision making can be considered. Energy consumption of pressurized irrigation methods has been studied recently using the up-to-date indices [Kartal et al. 2023]. These can be incorporated into the model as the third objective easily by specifying the necessary unit energy usage parameter and the decision variable to keep track of the energy consumed. Last but not least, scheduling actual water forwarding [Senyigit and Arslan 2018] can also be generated using the outputs of this study in a sequentially integrated manner.

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ABBREVIATIONS AND SYMBOLS

AWA: National Administrative Water Agency (DSI in Turkish)

FAO: Food and Agriculture Organization of the United Nations

TAGEM: General Directorate of Agricultural Research and Policies

APPENDIX

Sets	
Symbol	Definition
S	Set of scenarios generated connected to stochastic parameters, denoted by s
C	Set of crops that is planted in the region, denoted by c
P	Set of periods, 10 days; denoted by p
F	Set of farmers, denoted by f
Decision Variable (Main output)	
$X_{f,c,s}$, Represents the dedicated land to each crop type (c) by each farmer (f) for each scenario (s)	

Auxiliary (Decision) Variables	
$WaterCons_{c,s,p}$	Total water consumed as the result of scenario s by crop c during period p
$Revenue_{c,s}$	Total revenue earned by sale of the outputted crop c as the result of scenario s
$SavedWater_{s,p}$	Amount of water saved under the TargetWaterConsump (i.e. upper limit)
$ExtraNeed_{s,p}$	Amount of water required above the TargetWaterConsump (i.e. upper limit)
$BudgetDeficit_s$	Monetary value earned less than the $TargetReveue$ based on the resultant scenario
$ExtraGain_s$	Monetary value earned more than the $TargetReveue$ based on the resultant scenario
$MaxExtraNeed_p$	Maximum water amount needed above the TargetWaterConsump
$MaxBudgetDeficit$	Maximum budget deficit

Input Parameters	
Symbol	Definition
$dt_{c,s,p}$	Unit water consumption per period p by crop c (kg/m2)
$p_{c,s}$	Market price of crop c per (TL/kg)
$y_{c,s}$	Yield of crop c per (kg/m2)
$WeigthWater$(Revenue)	Value between (0,1) that represent the importance of total water consumption and revenue
$TargetWaterConsump$(Revenue)	Boundary values that set goals for total water consumption and revenue

- *Calculation of Total Farming Area* = Total farming land of the city (550883 ha)[6] * 33% (Proportion of the area focused within the region)=1.832.608.140 m2
- The *yield average* is obtained from the activity report of the city[7]
- *Calculation of target revenue* = Total value of vegetative production[4] * 33% (Proportion of the area focused within the region) = 1.151.141.640 TL
- *Market price* for the 2021 year per kg[8]
- Since the price and target revenue is set consistently using the *TL values of 2021* no conversion performed at the input level. The TL outputs can be transformed to 2023 values using the consumer price index change in the last 2 years[9]

[6] https://kayseri.tarimorman.gov.tr/Menu/29/Kayseri-Ve-Tarim;
[7] Activity report for 2021 by the Regional (Kayseri) Branch Farming and Forestry Ministry
[8] Turkstat, Agricultural Structure (Production, Price, Value) Publication; Turkstat,The Summary of Agricultural Statistics Publication
[9] https://data.tuik.gov.tr/Bulten/Index?p=Tuketici-Fiyat-Endeksi-Subat-2023-49656

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