UNIVERSITI PUTRA MALAYSIA

# *CROPPING PATTERN OPTIMIZATION FOR WATER RESOURCES ALLOCATION IN NEKUABAD IRRIGATION NETWORK, IRAN*

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# CROPPING PATTERN OPTIMIZATION FOR WATER RESOURCES ALLOCATION IN NEKUABAD IRRIGATION NETWORK, IRAN

By

HAMIDREZA SALEMI

Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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## DEDICATION

To my father, my mother, my brothers and my sisters who had helped me built the bridge

To my beloved wife, Simin and my twins, Bahar and Babak who had helped me finished and cross the bridge

Hamidreza Salemi

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctoral of Philosophy

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**JUNE 2012**

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**Faculty: Engineering**

During the last three decades in Iran, a high population growth rate had resulted in an increase in acreage and yield of summer crops with subsequent reduction in the fallow lands. Significant change occurred in the trend of cropping patterns towards crops with lesser water requirements from the limited water resources. Against this background a multi-criteria strategy is needed to improve the productivity of water and solve some major problems in the Nekuabad irrigation network located in the central part of Iran. The main aim of this study was to develop a multi-dimensional model that can optimize a cropping pattern not only to maximize the net benefit, agro-economic water productivity (net return to the volume of water used) and labor employment but also minimizing water consumption and total nitrate leaching.

The $ET_o$ calculator software which calculates $ET_o$ using the long term weather data as input to the Penman-Monteith equation was used. Then, net crop water requirements were calculated with the AquaCrop model. The potential of the AquaCrop model in deficit irrigation practice for seven main crops in dry area of Nekuabad irrigation network were studied. A set of second-order, seasonal crop water production functions were developed using the multi-crop simulation model for each crop in the study area. Ultimately, allocations of cropped area and irrigation water were made at seasonal levels through non linear deterministic programming, considering economy, social and environmental aspects. In this way, four critical objective functions subjected to a number of constraints with the use of the general algebra modeling system program were proposed for optimal cropping pattern in dry, wet and normal climatic conditions. These functions were then applied to the predicted optimal cropping pattern and optimal allocated water.

In the previous research using linear programming models, for each crop, fixed deficit irrigation ratio alternatives were imposed as input and the models compute optimal water and cropped area. In this study however, for each crop, crop water production functions ranging from 100 to 60% irrigation levels have been applied in the non linear programming model and the model computes the optimum irrigation volume ratio.

The calibrated AquaCrop model performed well under full and water stress conditions to predict crop yields, biomass and canopy cover. The coefficient of determination of the regressed crop water production equation showed good correlation between applied water and yield for all the crops. After optimization of the cropping patterns, the highest agro-economic water productivity in the irrigation network was found for potato in the dry year, followed by potato, rice and silage maize. The highest magnitude of global agro-economic water productivity was for the dry season followed by normal season and wet season. The results show that an increase of 116.8 % in net income is attained according to the model for the entire Nekuabad network. A 19.8 % increase in labor employment in wet season was found as compared to the current situation. There was 11% decrease in nitrate leaching for dry season as compared to the current situation. The total optimal amount of applied irrigation water in the study area can be reduced by up to 16.3 % for dry periods. These results demonstrated considerable improvements for the entire Nekuabad compared to the current condition. Cropped area of rice with high water demand decreased as compared to current condition. In contrast, potato and silage maize areas with relatively low water requirement increased. This shows that the multi dimensional model developed in this study has successfully optimized the water allocation in the study area regarding economy, unemployment and pollution aspects.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENGOPTIMUMAN CORAK TANAMAN UNTUK PENGAGIHAN SUMBER AIR DALAM RANGKAIAN PENGAIRAN NEKUABAD, IRAN**

Oleh

**HAMIDREZA SALEMI**

**JUN 2012**

**Pengerusi: Profesor Mohd, Amin Mohd Soom, PhD, P. Eng.**

**Fakulti: Kejuruteraan**

Dalam tempoh tiga dekad yang lalu di Iran, kadar pertumbuhan penduduk yang tinggi telah menyebabkan peningkatan dalam hasil keluasan dan tanaman musim panas dengan pengurangan berikutnya dalam tanah yang terbiar. Perubahan yang ketara telah berlaku dalam corak tanaman terhadap tanaman yang mempunyai keperluan air yang rendah dari sumber air yang terhad. Dengan latar belakang ini, strategi multi-kriteria adalah diperlukan untuk meningkatkan produktiviti air dan menyelesaikan beberapa masalah utama dalam rangkaian sistem pengairan Nekuabad yang terletak di bahagian tengah Iran. Tujuan utama kajian ini adalah untuk membangunkan model pelbagai dimensi yang boleh mengoptimumkan corak tanaman bukan sahaja untuk memaksimumkan faedah bersih, produktiviti ekonomi air pertanian (pulangan

bersih kepada jumlah air yang digunakan) dan penggunaan buruh tetapi juga mengurangkan penggunaan air dan jumlah larut resap nitrat.

Perisian pengira $ET_o$ yang menghitung $ET_o$ menggunakan data cuaca jangka panjang sebagai input terhadap persamaan Penman-Monteith telah digunakan. Kemudian, keperluan air bersih tanaman dikira dengan model AquaCrop. Potensi model AquaCrop dalam amalan pengairan defisit untuk tujuh tanaman utama di kawasan kering rangkaian sistem pengairan Nekuabad telah dikaji. Satu set tertib kedua, fungsi pengeluaran air tanaman bermusim telah dibangunkan dengan menggunakan model simulasi pelbagai tanaman untuk setiap tanaman di kawasan kajian. Akhirnya, peruntukan kawasan tanaman dan air pengairan telah dibuat mengikut musim melalui pengaturcaraan berketentuan tak lelurus dengan menimbangkan aspek ekonomi, sosial dan alam sekitar. Dengan cara ini, empat fungsi objektif kritikal yang tertakluk kepada beberapa kekangan dengan penggunaan pemodelan Sistem Pemodelan Algebra Am telah dicadangkan untuk corak tanaman yang optimum dalam musim kering, keadaan basah dan iklim yang biasa. Fungsi ini telah digunakan untuk corak penanaman optimum yang diramalkan dan pengoptimuman air yang diperuntukkan.

Dalam kajian sebelum ini, yang menggunakan model pengaturcaraan lelurus bagi setiap tanaman, nisbah pengairan alternatif defisit tetap telah digunakan sebagai input dan model itu telah mengira air yang optimum dan kawasan tanaman. Walau bagaimanapun, dalam kajian ini, bagi setiap tanaman, fungsi pengeluaran air tanaman yang terdiri dari 100 hingga 60% paras pengairan telah digunakan dalam model pengaturcaraan tak lelurus bagi mengira nisbah isipadu pengairan optimum.

Model AquaCrop yang ditentukur berprestasi baik dalam keadaan pengairan penuh dan keadaan kekurangan air untuk meramalkan hasil tanaman, kanopi menutupi dan biojisim. Pekali penentuan regresi persamaan pengeluaran air tanaman menunjukkan korelasi yang baik antara air yang digunakan dan hasil untuk semua tanaman. Selepas pengoptimuman, produktiviti pertanian ekonomi air pertanian tertinggi telah ditemui dalam rangkaian pengairan untuk corak tanaman ubi kentang dalam tahun kering, diikuti oleh kentang, padi dan jagung silaj. Keputusan model, menunjukkan magnitud tertinggi produktiviti ekonomi air pertanian global adalah untuk musim kemarau yang diikuti dengan musim biasa dan musim basah. Hasil kajian menunjukkan bahawa peningkatan 116.8% dalam pendapatan bersih telah dicapai mengikut model tersebut untuk seluruh rangkaian pengairan Nekuabad. Peningkatan sebanyak 19.8% dalam pekerjaan buruh pada musim basah telah diperolehi berbanding dengan keadaan semasa.Terdapat penurunan sebanyak 11% pada larut lesap nitrat untuk musim kemarau berbanding dengan situasi semasa. Jumlah optimum penggunaan air pengairan di dalam kawasan kajian boleh dikurangkan sehingga 16.3% bagi musim kering. Keputusan ini menunjukkan penambahbaikan besar bagi seluruh Nekuabad di bandingkan dengan keadaan semasa. Kawasan padi dengan permintaan air yang tinggi telah menurun berbanding dengan keadaan semasa. Sebagai perbandingan kawasan ubi kentang dan jagung silaj dengan keperluan air yang relatif nya rendah telah meningkat. Ini menunjukkan model multi-kriteria yang dibangunkan telah berjaya mengoptimumkan pengagihan sumber air berasaskan aspek ekonomi, penganggur dan pencemaran alam sekitar di kawasan kajian.

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| | |
|---|---|
| AW | Applied water |
| AWP | Agroeconomic water productivity |
| B | Biomass |
| Bd | Bulk density |
| CC | Canopy cover |
| CCo | Initial canopy cover |
| CDC | Canopy decline coefficient |
| CGC | Canopy growth coefficient |
| CWPFs | Crop water production functions |
| DAS | Days after sowing |
| DBY | Dry bulb-yield |
| DI | Deficit irrigation |
| Es | Evaporation from soil surface |
| ET | Evapotranspiration |
| $ET_o$ | Reference evapotranspiration |
| EWP | Economic water productivity |
| FAO | Food and agriculture organization |
| FPM | FAO Penman-Montieth |
| FC | Field capacity |
| GAMS | General algebraic modeling system |
| GDD | growing degree days |

| | |
|---|---|
| GWR | Gross water requirement |
| GY | Grain yield |
| HI | Harvest index |
| $HI_o$ | Reference harvest index |
| I | Irrigation water |
| IWMI | International water management institute |
| LAI | Leaf area index |
| LB | Left bank |
| LE | Labor employment |
| LP | Linear programming |
| MCM | Million cubic meters |
| MO | Multi-objective |
| MOP | Multi-objective programming |
| NK | Nekuabad |
| NLP | Non linear programming |
| NR | Net return |
| NWR | Net Water requirement |
| P | Precipitation |
| PWP | Permanent wilting point |
| RAW | Readily Available Water |
| RB | Right bank |
| SA | Sensitivity analysis |
| SM | Saturated moisture |
| S-M | Silage maize |

| | |
|---|---|
| SWC | Soil water content |
| TNL | Total nitrate leaching |
| Tr | Crop transpiration |
| Trx | Maximum crop transpiration |
| TY | Tuber-yield |
| UTM | Universal transverse Mercator |
| WP | Water productivity |
| Y | Yield |
| ZR | Zone root |
| ZRB | Zayandehrud river basin |

# CHAPTER 1

# INTRODUCTION

## 1.1 General

The forces of survival and the need for additional food supplies require a rapid expansion of irrigation in the world. In many areas of the world, the available water supply is restricted and expensive, which makes it impossible to irrigate the farmlands. In these situations, farmers must choose between full irrigation in a small area for maximum yield and reduction in the depth of water applied per unit area to increase the amount of cropped area. The latter policy is called deficit irrigation, which reduces crop yield per hectare but increases the net return per cubic meter (Kibe et al., 2006). The available water resources are consumed to meet the increasing water demands, and most river basins are now at the edge of developing to their maximum capacity.

In Iran, a developing country and subjected to frequent droughts and water shortages, the productivity of irrigation schemes could be improved by more efficient methods and management of existing water resources. Due to the lack of sufficient rainfall and unfavorable temporal and spatial distribution, Iran has been ranked among the arid and semi-arid countries in the world with serious problems. This is compounded by a high population growth rate during the last three decades that had caused an increase in water demand for the limited water resources. In order to obtain maximum efficiency from the constructed irrigation networks, it is required that the flow control system shall be operated to meet the crop water demand rather than on some previously fixed irrigation schedules. Agriculture in Iran is highly dependent on the irrigation water, as around 80% of the agricultural product comes from irrigated crops (Salemi et al., 2011). In Iran, producing enough food to better feed the people and generate adequate income for the farmers is a great challenge. This challenge is likely to intensify, considering population growth that is projected to increase to 100 million by 2030. Irrigated agriculture is an important contributor to food supplies and plays a major role in supply of food for the growing population. However, irrigation accounts for about 72% and 90% of the globe and developing-countries water withdrawals, respectively. Considering rapidly increase in demand of water for industry, domestic and environmental purposes water availability for irrigated agriculture will be less in future in many part of the world, especially in the arid and semi-arid regions. With growing demand for water in agriculture and in order to fulfill food security objectives, and moreover competition across water-using sectors for more water, has faced of Iran with the challenge of producing more food with less water. This goal will be met only if appropriate strategies are sought for water savings and for more efficiently use of water in agriculture.

One important strategy is to better manage the water and increase the productivity of water (Molden et al., 2006). The determination of water productivity (WP) index in Iran is essential to obtain suitable methods for better water use in agriculture sector. The concept of WP has become increasingly important and is a measure of the effectiveness of water use in contrast to land productivity. One of the methods for increasing productivity of water consumed in the agriculture sector is through improved water demand management. In the case of agricultural WP there are different descriptions to be considered (Khaledi and Ehsani, 2005). The most common descriptions are "agricultural WP from the view point of crop yield or benefits". The concepts of these two descriptions are briefly as follows:

- Productivity from the view point of crop yield: According to this definition, the higher productivity of agricultural water means more production per unit volume of water.
- Productivity from the view point of financial definition: According to this description, the highest productivity of agricultural water is obtained from most benefit per unit volume of water.

In limited-water resources areas, particularly in developing countries, seeking a trade-off between full irrigating to maximize production and to reduce the amount of irrigation water applied per unit region (deficit irrigation, DI) is an interesting problem. Since water planners should consider water scarcity in their economical analysis of cropping patterns, it is suggested that special attention should be paid to selected crops which require less water, but while providing the same level of benefit. Salemi and Amin (2010) revealed that the inappropriate supply and demand in the Zayandehrud River Basin (ZRB) in central Iran have indicated a non-sustainable agriculture in the study area.

The allocation of water between different networks in the area should be related to the overall water supply estimated at the time canals were scheduled to be opened in April each year. If water supplies are about average or above, current water allocations appeared satisfactory and should be maintained. But in dry years, a more rigid reduction in discharges to all irrigation networks should be considered. This is a trade-off between productivity and net return (NR). Thus, it is needed to make an extensive study for increasing AWP and NR in Nekuabad (NK) scheme by optimum water allocation in the cropping pattern and applying irrigation water management. During the last few years, the volume of water provided by the main canal has been variable and not enough to fulfill all water demands in the agricultural area. Therefore strategies need to be developed in advance for distributing the allocated water resources and optimizing the cropping pattern.

## 1.2 Arid area agriculture

By 2025, population of Iran is expected to reach around 97 million. To meet the food demand of the growing population, grain production has to be raised from 34 million tons in the year 1999-2000 to 48 million tons by 2025 (Ahmadi, 2008). In 2005, the country has become self-sufficient in wheat production. This could not have been attained without putting much pressure on groundwater withdrawal (even in the arid areas of the country) and substituting cultivation of wheat for other cereals. Part of the needed water was supplied through building of numerous new dams, better water management, better cultivation practices, and other managements at the field level. Unfortunately, this self-sufficiency did not last long (was not sustainable) and in the drought of 2008 the country had to import wheat again (Ardekanian, 2005). In spite of all the efforts to mitigate the problem of water scarcity, reasonable management and judicious utilization of available water still need more planning and actions (Roohani, 2006). Considering the decrease of water resources, climate change and reduction of the share of agricultural allocation, improvement of AWP based on more production per unit of water used in ZRB is very vital. Furthermore, the conflict between agriculture, domestic and industrial sector is likely to shift towards increasing the urban share. On the other hand, the uncertainty in the hydrologic phenomena will add to the potential crisis. So, for the overall economic growth of the country, efficient management of water resources in the face of uncertainty is of great importance. Surface and groundwater provide critical water supplement for crop production in central Iran. Agricultural activities have several impacts on the environment such as land use changes, water and soil pollution and competition between natural ecosystem components and agricultural demands.

In a river basin, surface water is usually being controlled behind dams to provide agricultural water requirements. However, the storage of water in the upstream areas affects downstream users. Generally, in a river basin, water management is a challenge due to the following reasons:

- High spatial variability of land and water resources;
- Multiple uses of water resources;

- High diversity of stakeholders;
- Phases of basin development;
- River basins as sources and sinks of salts
- Links with wetlands, swamps and other natural ecosystem components.

Some of the general problems in arid area agriculture such as ZRB can be summarized as follows:

1. Increasing food demand due to growing population.
2. The amount of water to the agriculture sector is likely to be insufficient due to the increasing domestic and industrial needs.
3. The main hydrological planning problem in these basins is due to water resources deficit, which is aggravated by the high climatic variability (typical of arid climates).
4. The main problem in Iran's river basins is that the agriculture sector uses most of the water resources with low equitable contribution to the economic development.
5. Global warming leads to climate change, which consequently affects water resources, water and soil quality, soil moisture, evapotranspiration, rainfall frequency, type of precipitation and its intensity, and all of these, affect AWP directly or indirectly.

Some of the specific problems in arid area agriculture are as follows:

1. The future improvements in AWP seem to be limited by economic rather than undeveloped technological considerations. So, there is a need to focus on improving the economic gains of water application.
2. The most important problem is the lack of trade-off between different crops in the agricultural sector itself to improve AWP through the irrigation scheme.
3. There is lack of an appropriate simulation model to focus on the effects of water on yield of different crops. Water managers in the ZRB are providing water according to the farmers' request and available water in the Chadegan dam's reservoir without the knowledge of AWP in relation to profitability of the crops grown. Hence, there is an urgent need to provide an irrigation scheduling system that can benefit all stakeholders in the river basin.

There is water scarcity in many irrigation networks in the country. Values of the reported irrigation WP, compared with global figures, are very low (Akbari et al., 2008). One of the essential steps to increase WP is optimizing the cropping pattern and crop density. By using a multi-objective function optimization approach and developing a comprehensive optimum cropping pattern model, crop density and water allocation can be optimized. Due to these complexities of water management in the ZRB higher AWP is difficult to achieve. Traditionally, the agricultural sector has been blamed for deficit of water resources, since it is the major water user in the country. It is estimated that around 80% of available water is used for irrigation purposes. Within the agricultural sector itself, there is a need to adjust the existing cropping patterns to optimize the net return from water uses based on the limitation of available water. The main drawback in the existing management is that the agricultural sector has been using most of the vital water resources in the ZRB without considering expected economical output.

### 1.3 Statement of the problem

Although there are many aspects where the components of water-saving agriculture can be manipulated, such as water-saving irrigation and soil management, but improvements in the AWP of crops by cropping pattern optimization has not yet been fully achieved. The main problem that water-saving agricultural research has to solve is how to raise the water utilization rate and achieve a high yield in irrigated farms with minimum consumptive water. Although an understanding of WP is required to develop improved water management strategies, yet little is known about it in irrigated networks of the river basins in Iran.

Modeling studies using different software in agricultural practices is quite new in Iran. Many studies have been carried out during the last decade on various aspects of optimization models, but rarely have physiological and agro-economic analyses been integrated. For example, crop growth simulation models have been used by agricultural researchers (Kiani et al., 2003; Kiani et al., 2004; Soltani et al., 2005; Majnoni Haris et al., 2006; Sepaskhah et al., 2006) and optimization models for agricultural planning by economists (Torkmani and Khosravi, 2001; Asadpour et al., 2005; Solimanipouri et al., 2005).

To date, the previous researches done at agricultural optimization field on addressing WP issues has come about indirectly from those researches in the last decade to increase farm benefit. But this study focus on increase WP include the NR, improvement of occupation, and less water use that emphasize less nitrate leaching in the soil. The hypothesis tested in this research is whether or not optimization of the cropping pattern will lead to improved AWP and NR to irrigators in the NK irrigation network.

**1.4 Objectives**

There is need to assess serious technical issues in NK irrigation network when conflict between water supply and demand in a multiple-cropping irrigation schemes arises. The intent of this research is to develop a model that can optimize a cropping pattern to maximize the NR and labor employment (LE) and minimize applied water (AW) and total nitrate leaching (TNL).

The specific objectives are:

1. To study the current cropping pattern and assess current agro-economic water productivity levels of the study area.
2. To assess and predict crop yield under water deficit conditions

using the AquaCrop model.

3. To apply a multi-objective function optimization approach to develop an optimum cropping-pattern model and using General Algebra Modeling System (GAMS) software to solve the optimization problem.

This thesis aims to apply new techniques on different aspects of optimization constraints including NLP and MOP. As a new finding on deterministic optimization technique combined with a simulation approach and in order to fully understand it, a CONOPT solver proposed by Rosenthal (2008) was applied to solve the aforementioned quadruplet issues in the region simultaneously. This technique is significantly superior to conventional methods such as single and two objective methods which are based on only one or two of the decision variables.

### 1.5 Scope of the study

The scope of this research includes:

1. Selection of the major river sub-basin in ZRB with adequate agronomic and climatic data.
2. Collecting of hydrological and meteorological data, crops, soils, farming practices, and economic data.
3. Determining the parameters required as input data set for running the

simulation and optimization models. Calculating net irrigation water requirements using the AquaCrop model (without any water stress).

4. Calculating net irrigation water requirements using the AquaCrop model (without any water stress).
5. Calibration of water-stress model for simulation of essential parameters.
6. Providing local crop water production functions (CWPFs) (describe the relationship of grain yield (GY) response to different levels of applied water input) using simulation model outputs and field experiments for main staple crops.
7. Investigating the validity of simulation model using field experiments for each crop in the study area.
8. Optimization of the cropping pattern, crop density and water allocation for various hydrologic regimes.

**1.6 Limitations of the work**

The following six limitations to the present study:

1) For the study period, there have been variations to the production costs (both the fixed and variable ones) as well as to the sale prices of the agricultural products, which is due to the variations in the supply and demand situation in the market. As these variations are unavoidable, the

weighted average of the prices over the last 10 years was used in this study and the expected value. Value was calculated in this way.

2) Currently, the Iranian state is modifying the price of fuel and agricultural subsidies. Omission of subsidies will markedly impact the balance in the agricultural market during a long period in the future. These changes may be far beyond the normal variations which make it impossible to make appropriate provisions in advance.
3) To estimate net water requirement for major crops in the irrigation network, data on irrigation efficiencies for individual crops for a given climate across the network is required. Because of the lack of this data, irrigation efficiencies measured for experimental farms by other researchers were used instead.
4) In estimation of annual depletion from groundwater resource there have been some errors from a number of boreholes, illegal operation of boreholes or the ones without permission for operation. An average estimated is made in view of this predicament.
5) Currently, data collection concerning the cultivated area for individual crops is achieved on the basis of district or village classifications. Apparently, this method will not result in high accuracies estimation of the cultivated area within the irrigation network.
6) The required climatic parameters for calculation of $ET_o$ were obtained from two synoptic meteorology stations (Kabutarabad and Najafabad). To compute this basic parameter more precisely, more weather station should be installed over the network.

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