# Regional Scale Irrigation Scheduling using a Mathematical Model and GIS

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**Abstract:** A user – friendly software that contributes to the regional scale irrigation scheduling is presented. Its ability to produce coloured maps of irrigation water needs is derived from the solution of the Richards equation by the numerical model SWBACROS, which was integrated into the ArcGIS environment. The study region should be densely sampled in order to be divided into texture and crop homogeneous sub-regions. Spatial variability of the soil hydraulic parameters inside each sub-region is handled by applying the scaling method to the set of point measurements contained within each sub-region. This paper describes the main theoretical considerations behind this software and compares two irrigation scenarios.

**Keywords:** GIS, irrigation scheduling, regional scale, Richards equation, scaling method.

## 1. INTRODUCTION

The use of water for irrigation is by far the greatest consumer of fresh water globally. Although irrigated regions of the planet occupy approximately 17% of the cultivated regions, they consume more than 70% of the world's water resources (Wolff, 1999). Saving just a small amount of the water destined for irrigation and using it for other purposes instead, (mainly drinking use) could improve the living conditions of millions of people. For example, in Morocco by transferring just 5% of the currently used irrigation water to drinking use is enough to almost double the amounts of drinking water (Wolff, 1999).

The use of mathematical models for the simulation of soil water movement in the unsaturated zone is a precise approach to rational irrigation and the key to irrigation water saving. Most of the mathematical models are simple water balance applications in contrast to the detailed mathematical ones that solve the partial differential equation known as the "Richards equation". Additionally the majority of the mathematical models do not take into account the spatial variability of the soil hydraulic parameters.

The combination of a detailed mathematical model, which solves the Richards equation, with some method of handling the spatial variability is therefore highly desired. If this could be done by a user-friendly graphical interface from inside a GIS software, then a regional water resources framework would be born. Using such a software would help the irrigation scheduling of a large agricultural area. In addition to saving fresh water meant for irrigation, the software would greatly contribute to (i) the preservation of the environment by reducing the surface and subsurface water resources pollution with agrochemicals and (ii) minimizing the degradation of soil quality due to the use of bad quality irrigation water.

The software in question, due to its increased requirements in specialized data, is not aimed at the farmer but rather to an organization that could provide irrigation advice services to the farmers. Such services, although well provided abroad, (Smith and Muñoz, 2002) are still lacking from Greece.

In this paper such a new software is presented. It was built in the Hydraulics Laboratory of the School of Agriculture of AUTh and can be used to schedule the irrigation of large agricultural areas. Its core is the mathematical model S.W.BA.CRO.S. (**S**oil **W**ater **BA**lance of a **CRO**pped **S**oil) model which interacts with ESRI® ArcGIS using code partly created in Visual Basic (VB) and partly in Visual Basic for Applications (VBA). The ArcGIS software extends the S.W.BA.CRO.S. capabilities and takes advantage of its accuracy, thus making it a valuable environmental decision support system for any organization in charge of operating collective irrigation networks. The reason is because it provides them with a way to achieve the sustainable management of irrigation water.

## 2. THEORETICAL CONSIDERATIONS

### 2.1. Mathematical Simulation

Computer simulation is a very useful and low cost tool for irrigation scheduling in the hands of managers of collective irrigation networks. Most of them follow the simplified water balance approach. A small number of them solve the well known and data demanding Richards equation (Richards, 1931). This partial differential equation describes the movement of water through unsaturated porous media, subject to appropriate boundary and initial conditions, while it accounts for the water uptake from the plant roots. The solution of this equation provides the depth distribution of soil water in a cultivated soil at one point in time.

The mathematical model S.W.BA.CRO.S. which is used in this software, solves the one-dimensional form of Richards equation using the Douglas-Jones predictor-corrector finite difference scheme (Douglas and Jones, 1963; Babajimopoulos, 1991;

Babajimopoulos, 2000). This implicit scheme has been proven to be one of the most satisfactory in simulating the one dimensional movement of soil water in the unsaturated zone (Haverkamp *et al.*, 1977; Babajimopoulos, 2000).

## 2.2. Description of Hydraulic Functions Spatial Variability

A very useful and practical method of describing the spatial variability of h(θ) and K(θ) functions is the scaling method (Miller and Miller 1955a; 1955b). According to this, the variability of a hydraulic parameter in a region is described by a parameter called scaling factor α which (i) is characteristic for each position and (ii) relates the measured values of hydraulic parameters in the sampling positions to the most representative (or "mean") value of the region.

The scaling method has been widely applied to problems that deal with the spatial variability of soil hydraulic parameters. Among other distinguished papers based on it, are those of Klute and Wilkinson (1958); Philip (1967); Warrick *et al.* (1977); Vogel and Cislerova (1993); Kelleners *et al.,* (1999) and Tuli *et al.,* (2001). A very good collection of publications may also be found in Hillel and Elrick (1990). An experimental investigation in the Greek language can be found at Georgoussis and Babajimopoulos (2006).

The simple approach of scaling theory was the reason for using it in this paper. The method used was proposed by Peck *et al.* (1977). According to this, for each location r (out of a total of R locations) of a soil layer k in a region, measurements ($h_i$,$S_i$) and ($K_i$,$S_i$) exist where S is the degree of saturation and i=1…I each step of degree of saturation. If we consider scaling factors $\alpha_{r,k}$ according to:

$$\alpha_{mean,k} = \frac{1}{R}\sum_{r=1}^{R}\alpha_{r,k} = 1 \tag{1}$$

then it can be shown that (Peck *et al.*, 1977**;** Ahuja *et al.*, 1984):

$$h_{mean,k}(S_i) = \frac{R}{\sum_{r=1}^{R}\left( 1/h_{r,k}(S_i) \right)} = \frac{R}{\frac{1}{h_{1,k}(S_i)} + \frac{1}{h_{2,k}(S_i)} + \ldots + \frac{1}{h_{R,k}(S_i)}} \tag{2}$$

and

$$K_{mean,k}(S_i) = \frac{1}{R^2}\left( \sum_{r=1}^{R}\sqrt{K_{r,k}(S_i)} \right)^2 = \frac{1}{R^2}\left( \sqrt{K_{1,k}(S_i)} + \sqrt{K_{2,k}(S_i)} + .. + \sqrt{K_{R,k}(S_i)} \right) \tag{3}$$

Afterwards the scaling factors can be estimated from:

$$\alpha^{h}_{r,k} = \frac{1}{I}\left[ \sum_{i=1}^{I} h_{mean,k}(S_i) / h_{r,k}(S_i) \right] \tag{4}$$

and

$$\alpha^{K}_{r,k} = \sqrt{\frac{1}{I}\sum_{i=1}^{I} K_{r,k}(S_i) / K_{mean,k}(S_i)} \tag{5}$$

## 2.3. GIS Integration Implementation

The aim of the present study was the creation of a software that can assist the farmers of a large region with diverse cultivations in deciding when and how much to irrigate their fields, taking into account the spatial variability of the hydraulic parameters of the soil. Integrated into the ArcGIS environment it can produce maps of irrigation water needs through a user-friendly interface and provide the user with the possibility of investigating various irrigation scenarios under different climatic conditions.

The application of the software in a region consists of various steps; the first being the division of the study region into sub-regions of common crops and common soil texture of the 0–30 cm and 30–60 cm depths. For example, such a homogeneous sub-region could be the “Cotton – Medium – Heavy” (coded as COT_MH) which is (i) cultivated with cotton (ii) the 0–30 cm texture is classified as of medium composition in the United States Department of Agriculture (U.S.D.A.) taxonomy system while (iii) the 30–60 cm is classified as of heavy composition. In order to do this division, the initial region is densely sampled. Afterwards the sand, silt and clay percentages are kriged in the well known ArcInfo extension Geostatistical Analyst which produces two layers of soil texture, one for each of the two depths.

Overlapping a third layer (the cultivation layer) onto the previous two, produces the final sub-regions whose “mean” hydraulic parameters are then found using the scaling method described in paragraph 2.2.

The necessary for the simulation meteorological data are gathered from the nearest weather station and can either be considered the same for the whole region or can be different for every sub-region (in case the climatic conditions of the region are monitored by more than one weather stations).

Simulation is then executed and the result is the mean root zone water content. This is compared to the field capacity and a user defined maximum allowed depletion limit, different for each sub-region.

It must be noted that the use of such a software demands that the user be an experienced agricultural engineer who can coordinate the collection of various input data, ranging from soil to plant and weather data.

## 2.4. User Interface

Using parts of VB6 and VBA code, a new toolbar has been added in ESRI® ArcGIS. For compatibility reasons version 9.x of ArcGIS should be used. The new toolbar gives the ability to carry out a single or multiple sub-regions simulation. After following some simple steps, the user can view the results (root depth mean soil water content – Figure 1) for the whole of the simulation period using a calendar (single region case – Figure 2) or by just taking a look at the coloured map (multiple region case – Figure 3).

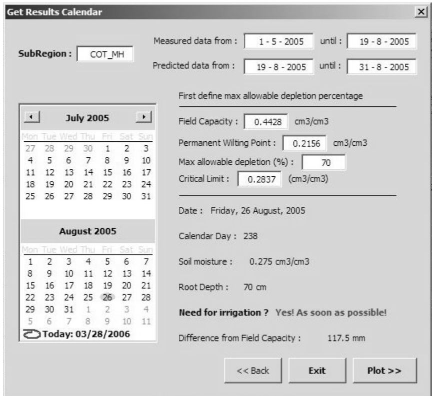


*Figure 1.* Viewing the simulation results of a specific sub-region.

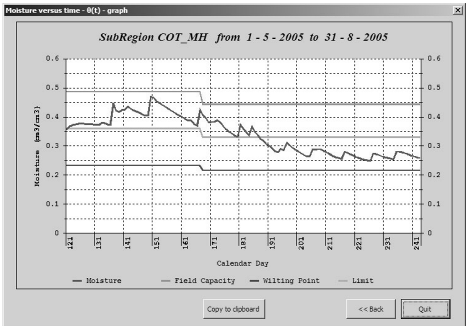


*Figure 2.* Root depth mean soil water content changes in a simulation period.

*Figure 3.* Visualization of the irrigation water needs of a specific day.

## 3. TEST APPLICATION AND SCENARIOS

The software was applied for testing and verification purposes to a 6302.1 hectare part of the Thessaloniki plain (Figure 4). This so called Halastra and Kalohori part is irrigated by a collective gravity irrigation network, whose waters are managed by the local land reclamation organization that is called "TOEB of Halastra and Kalohori".


*Figure 4.* Test region.

The test region has been densely sampled with a total of 625 sampling points (Figure 5) to determine sand, silt and clay percentages.

*Figure 5.* Dense sampling in test region.

Two scenarios were investigated for the test region: one using the real weather data of May to September 2004 and the second assuming a 10% increase in air temperature and 80% decrease in rainfall on the 2004 data. The aim was to investigate the effect of extreme weather conditions on irrigation scheduling of the existing cotton (COT), corn (COR), tomato (TOM) and alfalfa (ALF) fields.

The software ability to map the changes in soil water content can be demonstrated if irrigation is deliberately withheld for some days (Figure 6):

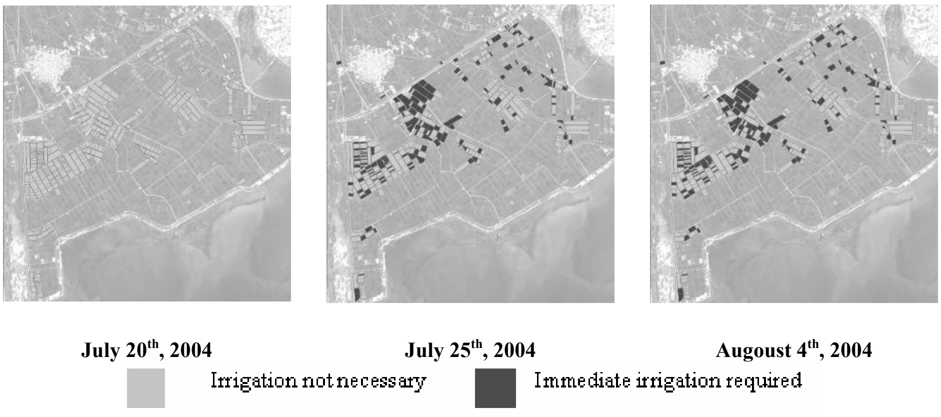


*Figure 6. Soil water decrease with time.*

Comparison of the irrigation scheduling of the two scenarios showed that the scenario weather data caused an increase in the amounts of applied water up to 58% more than the real 2004 data.

## 4. CONCLUSIONS

A GIS integrated software that contributes to regional irrigation scheduling has been presented herein. To achieve its goal, the initial region has been divided into homogeneous sub-regions. The mean hydraulic properties of each sub-region have been found using the scaling method. Soil water distribution – over time is presented via graphs or colored maps from inside ArcGIS 9.

Two scenarios were investigated after applying the software to part of the Thessaloniki plain using (a) the May – September 2004 weather and crop data and (b) data hypothetically showing an 80% decrease (-50.1mm) in rainfall with a concurrent 10% increase (+2.2°C) in the mean daily air temperature of the same period.

The rational irrigation schedule suggests an increase of 12% (for ALF_MH sub-region) to 77% (for COT_MM sub-region) in applied irrigation water, if the scenario weather data prevail in the region.

Improvements needed to the regional irrigation scheduling using this software are: (i) understanding the usefulness of such a kind of software and the necessity to disseminate the results of it to the farmers (ii) the increase in sampling points in order to improve the kriging estimates of sand, silt and clay percentages and consequently the delineation of sub-regions (iii) the increase in the number of points to determine soil hydraulic functions which consequently improves the "mean" functions estimates via scaling (iv) the integration of plant-water relations in order to fine tune the irrigation scheduling under insufficient irrigation conditions (v) programming of a variable in time maximum allowable depletion limit.

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