Applying Mathematical Models in Water Management and Irrigation Projects

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ABSTRACT

Modeling is increasingly being used in water resources and river basin management, primarily because of its enormous ability to store, analyze and display numerical and spatial data. Experts as well as researchers and users apply models and software products for simulation and solutions in a variety of commercial water projects and research studies over the worldwide for long years. The need for modeling was alerted by the complexity and complications of water problems, and necessity of determination of many involved parameters, through sophisticated steps. Feasibility, environmental friendly, and sustainability of agricultural/water systems required integrated vision and assessment. As the river basin has been acknowledged to be the major unit of analysis to address the challenges facing water management; modeling at this scale can provide essential aid for policy and decisions makers on water management and water allocation. Complexity and complication of eco-agricultural systems, determine the need for compiling system of models. Though this, there are several possible approaches for chaining mathematical models or coupling them with GIS platform, depending on the objective, data availability, models' resilience, and modeler skills. This paper outlines some methods and challenges related to applying mathematical modeling to simulate performance of water management projects. Review includes the "on-farm" and irrigation distribution network levels, regarding the impeded cropping, soil and environmental systems. This paper reviews the state of art of modeling selection and applications at canal and sub-basin network scales, with particular focus on the potential of coupled Agro-hydrologic models, presenting some modeling examples. For this, a comprehensive model survey, and reasonable model selection criteria were established. Furthermore; three successive modeling examples, developed by the author, were presented as: an On-Farm irrigation case on Songwe irrigation scheme (Tanzania) using model SIRMOD-III, an "Irrigation Network Operation" on RwimiRiver (Uganda) using (CANALMAN),and the third was applying an irrigation network module (CropMatch),developed by WMRI, in "Tanta Navigation Canal" assessment.

Particularly, in such cases, modeling of irrigation networks and eco-agricultural interventions became most effective to verify functionality, guess efficiencies, validate consistency, and to avoid design mistakes and environmental hazard. Also through modeling chains, it was possible to enhance design assumptions, optimize operation scenarios, and to specify quantities and costs. Further results were reached by modeling such as: risk assessments, and prediction of productivity, feasibility, and profitability of those projects.

Keywords

Mathematical modeling, Agro-ecological, water management, project

1. INTRODUCTION

“Mathematical Models” are one of the important types of the conceptual models that usually used in the analysis of natural and biophysical systems. The mathematical model simply depends on an equation, or a set of equations which represent the behavior of a system (France and Thornley, 1984). This type of the conceptual models could be given in different forms based on the formulation concept, inclusion of time variable, and probability (Table 1).

Thus, mathematical models could assimilate a powerful representation to different physical, chemical, biological, and even socio-economical relationships that determine the system behavior. These relationships could be translated into numerical manifestation, which could be easily functioned in computer simulation. As a general definition, “simulation” is the art of building mathematical or computer models of a system and using it to study the properties of the system in response to different scenarios (Rossiter, 2003).

Table 1. Basic Classification of Mathematical Models (Rossiter 2003, France and Thornley 1984)

Classification concept	Mathematical models types	Definition
Formulation Concept	Empirical	A model that relates predictions to data based on previous experience, with no attempt to model the physical causes. Used only for local applications, and valid for the same location of the row data and base lines.
	Mechanistic	A model that represents the physical causes of responses to conditions.
Time variable	Dynamic	A model where time is explicitly included, and the model predicts system state over time, that is driven by a time series of input data (usually weather)
	Static	A model that does not depend on a time series of input data.
Probability	Deterministic	A model that makes definite predictions for quantities without any association to probability distribution.
	Stochastic	A model that contain some random elements or probability distribution.

In water projects; mathematical models could be used most efficiently in:

- Pre-Feasibility studies and water resources assessment; to estimate water consumptions/ budget,
- Preliminary design of irrigation projects' Component and on farm systems (i.e. SIRMOD).
- Water system design models; design / simulate water systems (SHARK, HECRAS, SOBEK,…).
- Irrigation network simulation (like Crop-Match & Canal Man).
- Integrated simulation of "Eco-agriculture systems" and "agro-environmental systems" using complex system modeling (Multi-Agent Modeling Techniques; *Netlogo&GAMS*).

But, however, in presence of the numerous models that can be used for one purpose and with the escalating dependence on modeling for design, feasibility evaluation and management; it is not easy to properly select/use the most suitable model. Thus; this paper focuses on model selection as a prior critical step to satisfy research objectives, and to suit the internal and external system-environment**.** Further to development of "model selection criterion", effective examples for selection and application of the proper model were presented. Specifically, this research will offer a general survey and classification of models, that been commonly used in water management projects, review their features and capabilities, and weigh their performance and sensitivity in modeling assignments. Moreover, several examples are given for modeling studies in different cases at different stages of project evaluation. This included; outlining of an anticipated on-farm irrigation system (Songwe River irrigation scheme, Tanzania, 2014); simulation of an irrigation network performance (Rwimi Irrigation scheme, Uganda 2016);and assessment of an existing canal system performance to satisfy irrigation duties (WMRI, Tanta Navigation Canal 2012).

Thus, the research objectives can be listed as:

- Surveying and classification of the famous water management modeling tools
- Evaluate models according some standard scales
- Develop a model selection technique
- Presenting modeling examples on different modeling stages (outlining/designing, design verification, and performance evaluation)

2. METHODS AND DISCUSSION

Methodology includes: i) review, evaluation and classification of agro-irrigation models, ii) developing model selection and modeling approach criteria, iii) giving live examples for model selection and application.

2.1 Review and Classification of agro-irrigation models

Due to complexity of agriculture/irrigation system; the approach to "system structure complexity" was essential according to Wery (2014). Also Hierarchy theory should be considered when investigating such systems that operate on several "Spatio-Temporal" scales (Weston and Ruth, 1997). This is mainly concerned with the linking of models representing system parts of interest to the user (Tol, 2006). Any system under study should be clearly characterized in terms of its spatial and temporal scales, and its boundaries and components will depend on the extent of the study. Thus; the system structure should include system elements, relationships elements, borders, inputs/outputs, subsystems' detail, scale and goals. The given below is a schematic diagram for the standard modeling stages (Fig. 1).

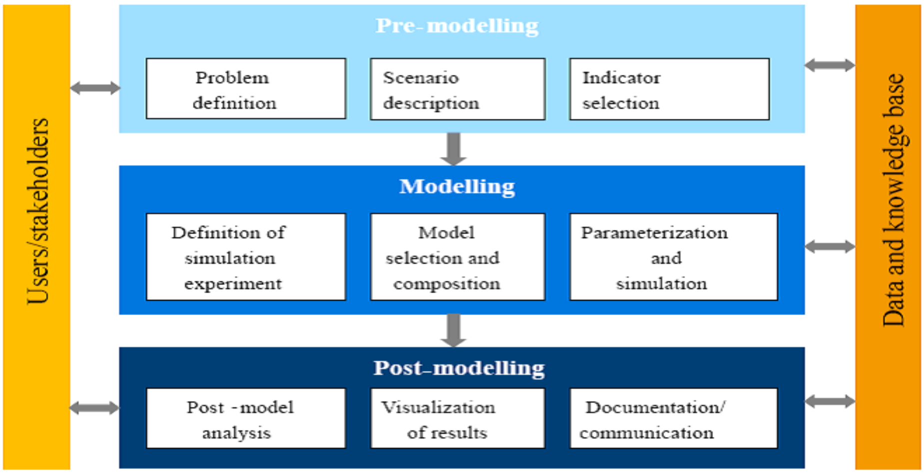


Fig. 1. Modeling Stages: Pre-Modeling, Modeling, and Post-Modeling

2.1.1 GIS Linkage Availability and Irrigation Models' Coupling (Network &Seepage Models)[i]

Geographic Information Systems (GIS) is increasingly being used in water resources primarily because of its ability to store, analyze and display spatial data. There are several possible approaches to coupling GIS with simulation models, depending on the objective, availability of data and resources, and the skill of the modeler. A few researchers have linked GIS with simulation models for irrigation management. For example, Gupta et al. (2003) used the interpolation techniques of *ArcInfo* to generate a topographic map of an irrigation command area in India. The digitized map data was then used as an input into hydraulic model. Ines, et al. (2002) used GIS and crop growth models to estimate irrigation water productivity. In cases, data analysis and model simulations were done external to GIS, and GIS was used to input and store spatial data, and to display results. Main issues and challenges include user considerations, proper geo-referenced data, GIS software cost, availability of skills, and the difficulties of coupling existing models with GIS.

2.1.2 Coupling Techniques

There are several possible approaches to coupling GIS with models, which vary depending on purpose, resources' availability, and modeler skill encompassing:

a. **Loosely coupled**: The simulation model is run independently of GIS, and linkage is achieved using external code, or via Visual Basic within ArcGIS.

b. Closely coupled models through a user interface: Models are linked to a GIS coverage data model through a user interface. For example, ArcGIS database is used to provide the site-specific information and/or to identify model data files that are required for model assembly.

c. Closely coupled through a relational database: A geo-database is a relational database that stores geographic data. At its most basic level, the geo-database stores encompass both spatial and attribute data and the relationship between them. These allow the user to build more complex data models including modeling the flow in geometric networks.

d. Modeling using GIS platform: Several tools are available in GIS platform to develop models and carry out spatial analysis. Examples include:

- Geo-statistical functions – used to interpolate surfaces based on the spatial location data. This is useful for interpolating geological variables such as rainfall, temperature, and hydraulic conductivity
- Distance functions that allow the user to determine the nearest location to a feature or the least cost path to a particular destination.

Out of many models, only HEC-RAS and HEC-HMS had the ability to import three-dimensional river schematic and cross section data created in a GIS or CADD (Computer Aided Drafting and Design) system. Then, after a hydraulic analysis is completed, the computed water surface profiles can be exported back to the GIS or CADD system.

2.2 Survey and Classification of Models applied in Irrigation and Water Management:

The following brief survey (table 2) summarizes applied models in water and agricultural systems comprising: Hydraulic, Agro-Ecological, Bio-Physical, and Bio-Economic models' Examples:

Table 2. Models Applied in Water and Agricultural Systems' modeling

Model Type	**Model Purpose & Capabilities**	**Model Example**	**Notification**
Hydrology	Hydrological Analysis & GIS Based Models (***DMS***&**WaterCAD** for Irrigation Schemes Planning**)**.Precipitation Models (**Rainbow)**, Surface Water **(HEC-HMS),** and groundwater (**MODFLOW).** Hydrological	**HEC-HMS, MODFLOW & RAINBOW**	By US Army Corp of Engineers, Hydrologic Engineering Center "HEC" (USACE, 2002).
Climatic Changes'	extract the projected changes in air temperature (□ air-temp), carbon cycle, aerosol forcing and ice melt	**MAGICC/SCENGEN**	C-cycle (Wigley et al., 2000)
Crop Consumptions (Etc) / Crop Uptake, & Irrigation Scheduling	Water Consumption Models**;** Eto, Crop Kc, Effective rain, Crop-water requirements, Total/Readily available moisture (RAM), Actual crop evapotranspiration "Etc", Daily soil moisture deficit, Irrigation interval (day) & irrigation depth applied (mm), irrigation Loss.	**CropWat**, **HIM-Bary Calc**.,&**ICARDA**tool	CropWat; By LAND and Water Development Division of FAO
	Mechanistic and deterministic models for simulation of unsaturated-saturated soil water flow; soil hydraulic properties, hydraulic conductivity, solutes movement, moisture extraction in root zone layers.	**1-D SWATRE**	By: Feddes et aI., 1978; Belmans et aI., 1983
	Agro-Cropping Models/Water Productivity Models: predicts plant water uptake, water and solute transport under irrigation/drainage systems, and the relationship between crop yield and water/Nitrogen use.	(**SALTMED**, &**Aqua-Crop**).	By: R.Ragab(2002), &Doorenbos and Kassam(1979)
Irrigation Design Models	On-Farm Surface irrigation system design/Assessment: Simulating hydraulics of surface irrigation systems at field level; Topography/ Geometry; Infiltration Characteristics, Design tables (numerical / plot results),and operation simulation indicators (i.e. runoff hydrograph).	(**SIRMOD**)	By; SCS National Engineering
Irrigation Design; Hydraulic Design, & Structural Design	Check design, Check Operation harms (scour/sediment) & maintenance/rehabilitation of interventions: design programs (DORC, DACSE and DOSSBAS, SHARK); cross sections evaluation for" Water depths, flow velocity, discharge, and geometry, hydraulic and sedimentation checks for design and maintenance purposes.	**HEC-RAS** & **SOBEK**	By the US Army Corp of Engineers, Hydrologic Engineering Center "HEC" (USACE).
	Flow Simulation; Canals & Hydraulic Structures evaluation; One-D hydraulic models; natural & artificial networks, graphic interface, Steady Flow Water Surface Profile Prediction [G.V. F], Handle full network, or single river reach, profile computations; multiple structures; bridge scour; spill flow; stable channel design. Unsteady Flow Simulation; regime calculations. Sediment Transport, Water Quality Simulation.	***SHARK***	
Up-scaling/Aggregation Models (Scheme	Scheme/Network discharge simulation models; (**IRDDESS**[ii]*****); crop growth and irrigation simulation model; predicts biomass development and yields for soil type & irrigation management scenarios, water demand and irrigation schedule in distribution system, water demand at field/ system: at canals' levels, decision	(***IRDDESS***); (Irrigation District Decision Support	Developed at Texas A & M University 1992-1995.

requirements & Network simulation models)	support for irrigation schemes.	System)	
	Water Requirements/ Management on Irrigation District Level models **(Crop-Match)**: Predicts water requirements for crop pattern gross (updated every 15 days), canals' duties, irrigation rotations, and district's water budget; counts for: soil type, canals' characteristics, and losses.	**(*Crop-Match*)**	M. SherifSaad, & A. Negm; WMRI, 2004.
	Network Aggregation performance and Canal Management Software packages (**CanalMan**); performing hydraulic simulations for1-D unsteady flow in canal networks, permits analysis, design, operational &training activities, Simulates canal operations to generate operating schedules. Results: flow depths, discharges, and control structure settings. Simulation results: Numerical and Graphical formats or tabular results.	(***CanalMan***)	CANALMAN by Merkley G.P.1997
	Feasibility and Performance Agro-Irrigation projects' and Water Productivity. **WP-Calc**. analyzes the performance of the tertiary to canal system by using three types of indicators; Crop-Water Productivity, Irrigation Efficiency, and Distribution Adequacy. **WP-Calc**. application has a major database consisting of the following groups of data; Metrology, Soil, Crop, Irrigation/Drainage Networks, & Groundwater. Outputs include: -irrigation Efficiency.-Crop Water Productivity (Canal, Mesqa, & Tertiary Levels –Irrigation Distribution Efficiency.	(***WP-Calc***)	**ICARDA, WMRI, & ARC (S. Attaher, 2014)**

2.3 Model Selection

Many models were frequently used for evaluating, designing, or simulating irrigation networks. Among those models, there were only few favorable to perform analysis. Therefore, a brief review is given below, to reveals each model's limits, capabilities, and advantages.

1. *Review of the models*: the models previously listed were subject to a comprehensive review in order to select the most efficient model/s that could comply with the objectives of the ongoing analysis, which differs by case. Besides conducting a comparison between the models, this review includes a comprehensive guide for using modeling in developing efficient irrigation management options.

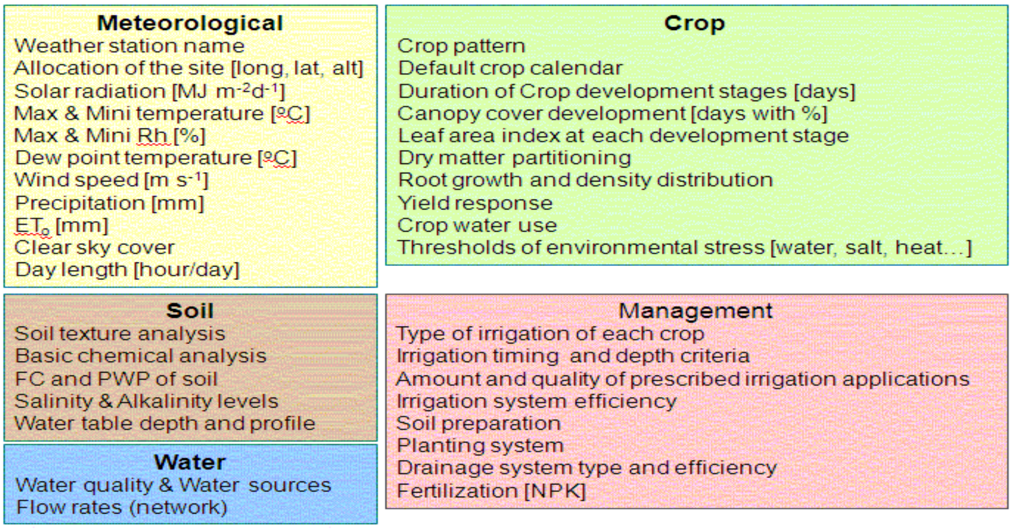
2. *Develop criteria for the modeling approach selection*: Developing evaluation criteria for model/s selection was one of the important technical activities. The developed criteria were focused on meeting the objectives of the study, the accuracy, and consistency of the evaluated model. The following points are the basic criteria used to evaluate the models:

a) Meeting the objective of the study, which could be as follow:
  - irrigation scheduling analysis,
  - crop-growth analysis,
  - water productivity analysis,
  - soil water flow, soil heat flow (water budget physical analysis),
  - salinity build-up in soil, or water salinity (quality) analysis (solute flow),
  - water stress,
  - salinity stress,
  - hydraulic interactions,
  - examine different scenarios of irrigation-management or nitrogen leaching on crop growth,

b) Accuracy of the theoretical bases used on the model,
c) Simulate crops,
d) Calibration requirements,
e) Model inputs, and validity for GIS Linkage
f) Consistency, and availability for Coupling with Other Models,
g) Model outputs format, consistency for up-scaling,
h) Simulation running strength,
i) Constrains and limitations of using the model,
j) License,
k) Interface simplicity,
l) Availability of scientific review, case studies and technical assistants.

2.4 Model Suitability

Through models evaluation procedure, a list of the common model inputs and system environment must be developed in an analytical manner as presented in the following figure. Models will, then, be assessed, compared, and reasonably selected. Calibration is a further step, required for model adaption after checking sensitivity and liability. Furthermore, a simple aggregated statistical index was developed to identify the compatible model/s that could be used in likely studies. This index is determining the overall compatibility based on the evaluation criteria developed before.



Meteorological
Weather station name
Allocation of the site [long, lat, alt]
Solar radiation [MJ $m^{-2}d^{-1}$]
Max & Mini temperature [ºC]
Max & Mini Rh [%]
Dew point temperature [ºC]
Wind speed [m s^{-1}]
Precipitation [mm]
ET_o [mm]
Clear sky cover
Day length [hour/day]

Crop
Crop pattern
Default crop calendar
Duration of Crop development stages [days]
Canopy cover development [days with %]
Leaf area index at each development stage
Dry matter partitioning
Root growth and density distribution
Yield response
Crop water use
Thresholds of environmental stress [water, salt, heat…]

Soil
Soil texture analysis
Basic chemical analysis
FC and PWP of soil
Salinity & Alkalinity levels
Water table depth and profile

Water
Water quality & Water sources
Flow rates (network)

Management
Type of irrigation of each crop
Irrigation timing and depth criteria
Amount and quality of prescribed irrigation applications
Irrigation system efficiency
Soil preparation
Planting system
Drainage system type and efficiency
Fertilization [NPK]

Fig. 2. Biophysical Model Inputs and the Main System Environment

The Index ranged between 0 (not compatible at all) to 1 (highly compatible). In the table below the results of evaluation for seven crop-models which have the highest values of compatibility index. It could be concluded that SWAP, SPAW and Crop-Syst models have the highest compatibility index values, and sensitivity due to analysis conducted by the "Bench Mark", ICARDA team as:

Table 3. Example Evaluation of Mathematical Models

Parameter	**CropWat**	**SIMETAW**	**SWAP**	**SPAW**	**CropSyst**	**DSSAT**	**AquaCrop**
1-Objective	7	5	9	9	8	5	5
2- Theory	6	4	9	8	7	4	4
3- Crops	6	5	8	8	8	8	6
4- Strength	5	2	10	10	10	5	5
5- constrains & limitations	6	2	8	8	8	5	5
6- inputs	9	9	8	8	9	9	9
7- outputs	5	5	10	10	10	5	5
8- license	0	10	10	10	10	10	10
9- Interface		6	9	8	6	6	9
10- The availability of scientific review, case studies and technical assistants	4	1	8	6	8	9	5
11- calibration		6	8	8	7	4	9
12- Error alerts & log files			9	9	5	9	5
Overall compatibility index	4.8	4.9	8.9	8.5	8.4	6.6	6.3

2.5 Models' Evaluation[iii]

As a start, a list of available models, that may meet the modeling objectives, was prepared, where models were classified based on: type, power, citation, and information availability. Then, models were classified in five types: crop growth models, crop-water models, water budget models, decision support models, and Hydrological models. Table 4 classifies models, summarizing the famous water management models into three main groups;

among which user can select the most proper model to his case, according to modeling stage and available data.

Table 4. Model Types: References Availability and Applications

Model	Information fulfillment	Model type
1- WAVE	X	Crop-water model
2- SIMETAW	X	Crop-water model
3- Yield_stress	X	Crop-model
4- CropSyst	XXX	Crop-water model
5- DSSAT	XXX	Crop DSS model
6- SALTMED	XX	Crop-water model
7- AquaCrop	X	Crop-water model
8- CropWat	XXX	Crop-water model
9- SWAP	XXX	Water budget model
10- SPAW	XX	Water budget model
11- WEAP	XXX	Water balance DSS model
12- CropMatch	XXXX	Water Budget (Canal) model
12- SIWARE	XXX	Hydrological model
13- SIRMOD	XXX	Hydrological (on-farm) model
14- IRDDESS	XXX	Hydrological model
15- HEC_RAS	XXX	Hydrological model
16- CANALMAN	XXX	Hydrological model
17- DMS	XXX	Hydrological model

2.6 Model Validation and Uncertainty Analysis

However, there were always unavoidable uncertainties associated with mathematical modeling. Willems and Berlamont 1999 demonstrated a number of uncertainties involved in the modeling of a sewer system, including those relating to data inputs, model simplifications of the physical reality, and uncertainties. There are a number of possible ways to reduce the residuals and improve the performance of such models. The obvious approach is to address directly the deficiencies in the deterministic model and improve the accuracy of its physical representation of the system being modeled i.e., improve the system geometric description and/or the physical equations describing system operation. However, increasing the model complexity does not always produce better performance due to data limitations, uncertainty, and estimating difficulties. Fundamentally, there are four sources of uncertainty: Incomplete information, Disagreement between information sources, Linguistic imprecision, and Variability.

Some factors are necessarily uncertain because they are indeterminate. Sometimes, a factor may not be practically measurable. The fourth source of uncertainty, variability, simply refers to change. Parameters which change over time (for whatever reason) can give rise to uncertainty.

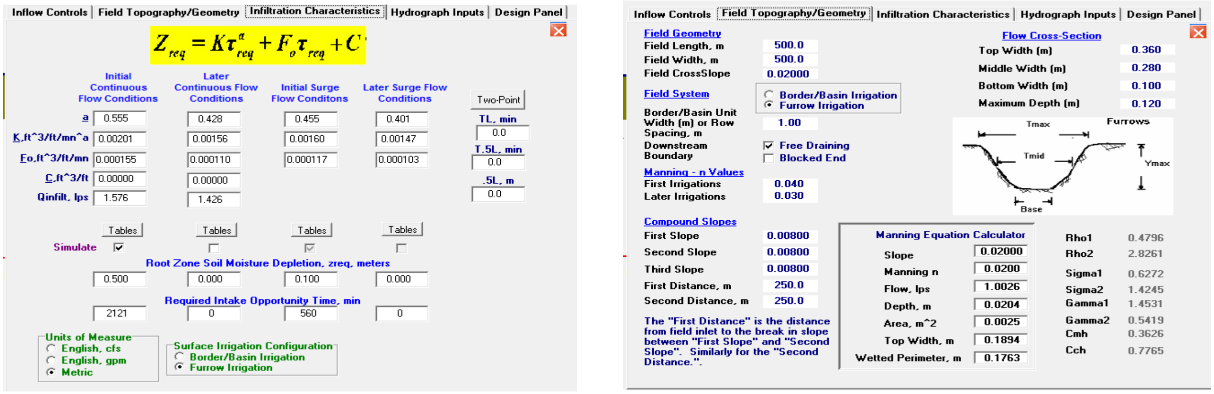
3. RESULTS ON APPLYING MATHEMATICAL MODELS AND PACKAGES TO WATER PROJECTS

Over the past decades, there has been much research in developing computer models and software packages for water resources planning and management (Wurbs, 1994). However, there has been little work on modeling of irrigation distribution networks, and most existing models lack GIS database connectivity. The most widely known distribution models included:

- Water requirements and Water Budget models.
- Steady-state canal hydraulic model (Merkley, 1993)
- Unsteady - hydraulic model for branching canal networks (CanalMan; Merkley, 1997)
- River hydraulic models of 1-D steady and unsteady flows (Brunner, 2001). To present practical examples for model application and to verify its importance in agro-ecological projects; several case studies are presented below to reveal basis of model selection and model application.

1- Case Study 1; On-Farm Irrigation System Simulation (SIRMOD)

In Lower Songwe River (Tanzania), to ensure efficiency of the tertiary network design and planning; an On-Farm Irrigation modeling test was carried out using (SIRMOD III). The model was selected upon the developed criteria, to meets the case requirements (table 2, Model 6). The approved on-farm system contained flood furrow and basin irrigation systems for 500 m x 500 mparcels. The model enquired specifications of soil, metrological, and water application frequency, before configurations of land planning and irrigation/drainage features and controls'. The given below is the main model settings.



$$Z_{req} = K\tau_{req}^{a} + F_o\tau_{req} + C$$

	Initial Continuous Flow Conditions	Later Continuous Flow Conditions	Initial Surge Flow Conditons	Later Surge Flow Conditions
a	0.555	0.428	0.455	0.401
K,ft^3/ft/mn^a	0.00201	0.00156	0.00160	0.00147
Fo,ft^3/ft/mn	0.000155	0.000110	0.000117	0.000103
C,ft^3/ft	0.00000	0.00000		
Qinfilt, lps	1.576	1.426		
Simulate	☑	☐	☑	☐
Root Zone Soil Moisture Depletion, zreq, meters	0.500	0.000	0.100	0.000
Required Intake Opportunity Time, min	2121	0	560	0

TL, min 0.0
T.5L, min 0.0
.5L, m 0.0

Units of Measure
○ English, cfs
○ English, gpm
● Metric

Surface Irrigation Configuration
○ Border/Basin Irrigation
● Furrow Irrigation

Field Geometry
Field Length, m 500.0
Field Width, m 500.0
Field CrossSlope 0.02000

Field System
○ Border/Basin Irrigation
● Furrow Irrigation
Border/Basin Unit Width (m) or Row Spacing, m 1.00
Downstream Boundary ☑ Free Draining ☐ Blocked End

Manning - n Values
First Irrigations 0.040
Later Irrigations 0.030

Compound Slopes
First Slope 0.00800
Second Slope 0.00800
Third Slope 0.00800
First Distance, m 250.0
Second Distance, m 250.0

The "First Distance" is the distance from field inlet to the break in slope between "First Slope" and "Second Slope". Similarly for the "Second Distance.".

Flow Cross-Section
Top Width (m) 0.360
Middle Width (m) 0.280
Bottom Width (m) 0.100
Maximum Depth (m) 0.120

Manning Equation Calculator
Slope 0.02000
Manning n 0.0200
Flow, lps 1.0026
Depth, m 0.0204
Area, m^2 0.0025
Top Width, m 0.1894
Wetted Perimeter, m 0.1763

Rho1 0.4796
Rho2 2.8261
Sigma1 0.6272
Sigma2 1.4245
Gamma1 1.4531
Gamma2 0.5419
Cmh 0.3626
Cch 0.7765

Figure 6. SIRMOD Set-up, and Data Input

To achieve reliality of the scheme operation upon the proposed planning, the dominant operation parameters must be adjusted to fullfil the desired system performance (fig. 6).Model run had stuked due to conflict due to parcel size, insufficiency of assigned irrigation period, or application rate (or both). Thusiterations are essintial to adjust farm sizing, application rates/ duration (see fig. 7).

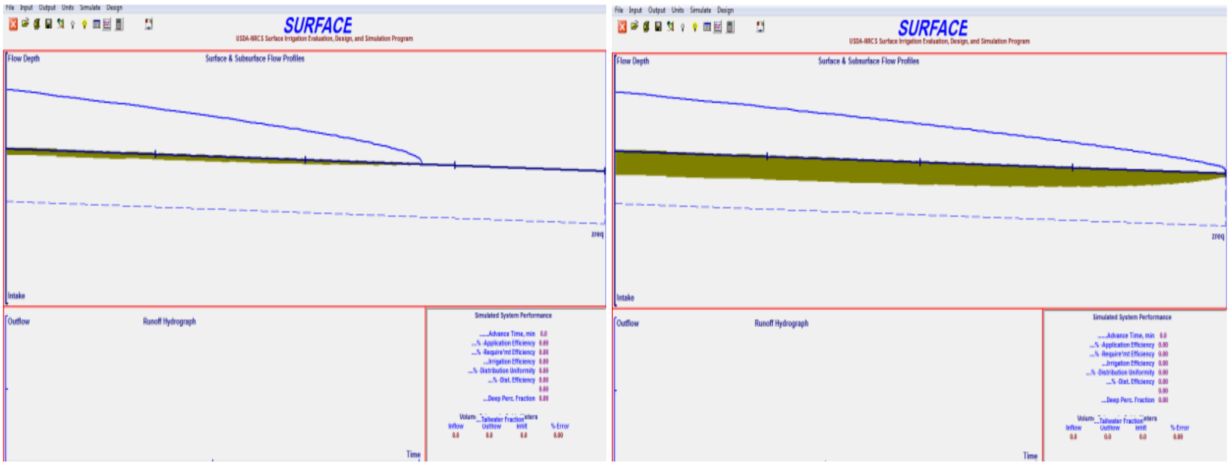


Figure 7. SIRMOD Preliminary Run: Water Surface and Saturated Depth Simulation Results

Second Trail;Regarding the model response; trial (2) was achieved changing the farm planning (500 x 250 m), using the same settings for furrows, slopes, flowrate, and increasing duration (24 hours). Due to farm sizing and irrigation time adjustments; finer results are presented in fig. 8.

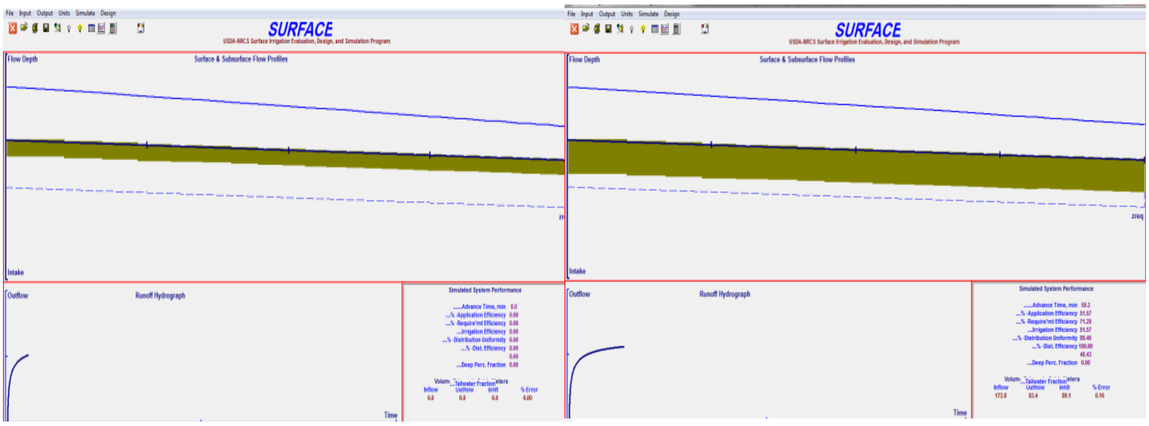
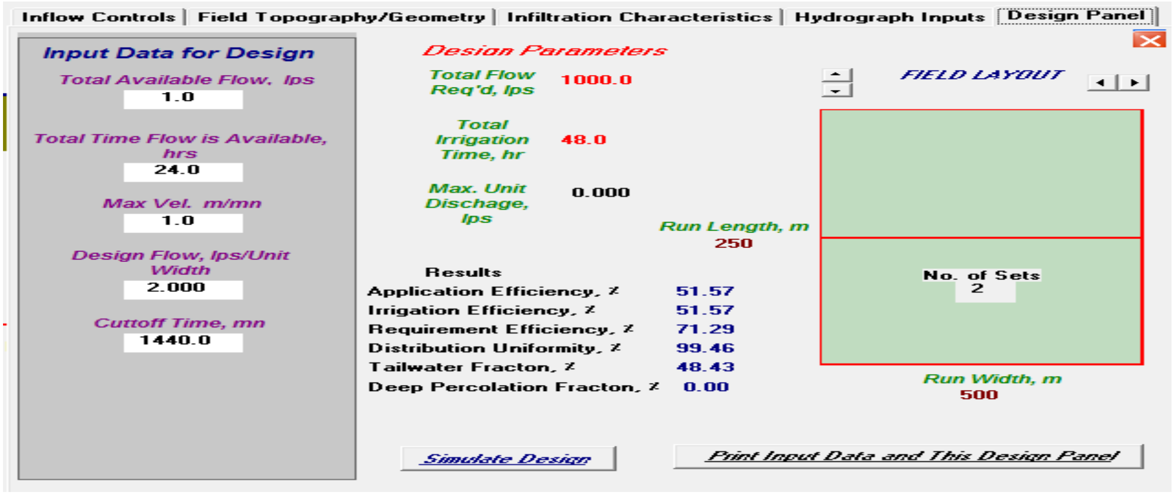


Figure 8. Second Trial; Water Surface Progress, and Soil Saturation Results

The model finished run successfully, and the resultant planning and configurations were reliable. The obtained results from simulation are as given in fig. 9.



Input Data for Design

Total Available Flow, lps 1.0
Total Time Flow is Available, hrs 24.0
Max Vel. m/mn 1.0
Design Flow, lps/Unit Width 2.000
Cuttoff Time, mn 1440.0

Design Parameters

Total Flow Req'd, lps 1000.0
Total Irrigation Time, hr 48.0
Max. Unit Dischage, lps 0.000
Run Length, m 250
No. of Sets 2
Run Width, m 500

Results	
Application Efficiency, %	51.57
Irrigation Efficiency, %	51.57
Requirement Efficiency, %	71.29
Distribution Uniformity, %	99.46
Tailwater Fracton, %	48.43
Deep Percolation Fracton, %	0.00

Figure 9. On Farm Simulation Results, and Parcel Size Justification

Conclusions of On-Farm IRRIGATION Modeling:

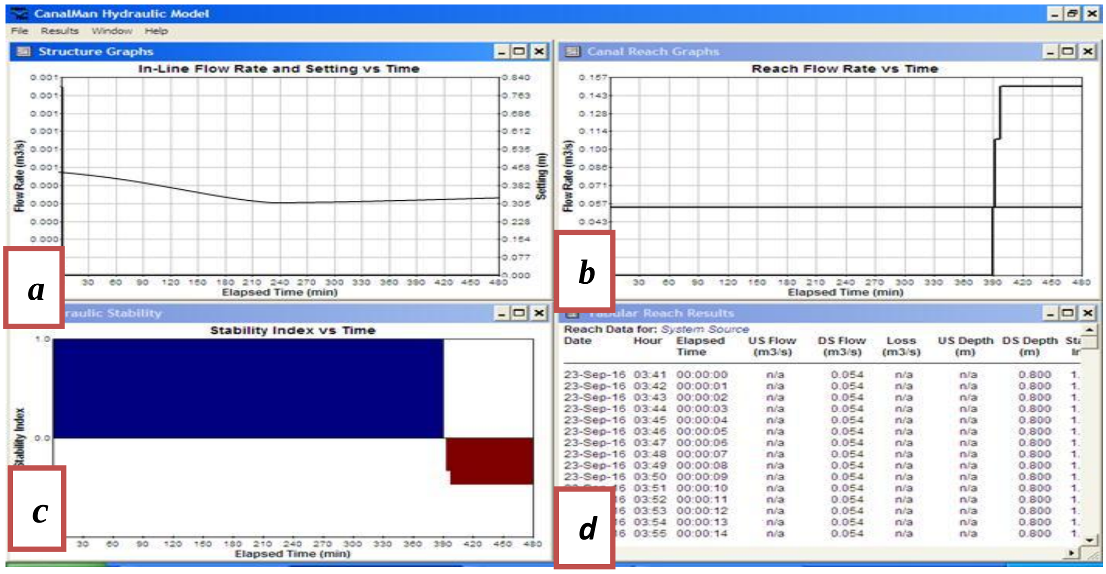
1. The best economic design for agricultural parcel (for minimizing infrastructure costs and excavation and structures); is the 500 x 500 m parcel, to enable an adequate spacing between open channels and drains and good drainage duty between tertiary drains, as well as avoiding seepage and water logging due to near tertiary canals.
2. Parcel length and furrow size had affected the irrigation efficiency and elapsed time for satisfying tail end, and wetting root zone. Therefore, parcel should be divided at least into two basins of 250m length, to ensure good efficiency and water saving.
3. The best scenario (for "Cassava"; root zone = 1.0 m), was obtained when applying rate of 2 l/s/ha.
4. An internal water rotation system could be applied comfortably, to maintain the system on a moderate working capacity, to conserve resources (saving water and avoiding soil logging), and to maximize efficiencies of water use and crop productivities.

2- Case Study 2; Network Modeling; Examples of *CANALMAN* model application

A modeling study was carried out to demonstrating the performance of an anticipated supplementary irrigation network in Uganda in Rwimi irrigation scheme. In addition it was required to provide an operation simulation for water distribution along the irrigation network. The given below is the applied modeling example.

Optimization of Water Use and Canal Network Operation in *Rwimi* Irrigation Scheme, Uganda

A supplementary irrigation scheme was assigned to be designed by the author (in 2015) in Rwimi River basin, west-Uganda (*Rwimi Prison Farm* N 0.3857940, E 30.1902690, and elevation 1178). The project targeted construction of a headwork, integrated irrigation open channels' network, and a tertiary system to serve about 1000 ha. The technical evaluation work was executed to evaluate hydraulic performance of the proposed irrigation system in RwimiRiver basin, Uganda. Repetitive testing of influence of a wide variety of design parameters and hydraulic assumptions was made. The one-dimensional hydrodynamic model CANALMAN[iv] was applied to real data from RwimiBasin, to study its hydraulic performance. Extensive field data was collected to evaluate the physical & hydraulic parameters needed to calibrate the model. Effect of changes in roughness values (Manning's constant) was evaluated. The system performance was tested for design discharges to check liability, and for emergency (flood) discharge to check safety. It was observed that appreciable amount of water could be saved using some operation alternatives recommended in the technical appraisal report. The given figures represent model running, and simulation of the network performance under operation. Figure (10) shows specific operation indicators including: in-line and reach flow rates vs. time, and Hydraulic Stability Indexv. Figure (11) presents water surface, and slopes for feeder canal and branches in operation for "Rwimi" irrigation network due to CANALMAN Simulation results.



Reach Data for: *System Source*

Date	Hour	Elapsed Time	US Flow (m3/s)	DS Flow (m3/s)	Loss (m3/s)	US Depth (m)	DS Depth (m)	Sta Ir
23-Sep-16	03:41	00:00:00	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:42	00:00:01	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:43	00:00:02	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:44	00:00:03	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:45	00:00:04	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:46	00:00:05	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:47	00:00:06	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:48	00:00:07	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:49	00:00:08	n/a	0.054	n/a	n/a	0.800	1.
23-Sep-16	03:50	00:00:09	n/a	0.054	n/a	n/a	0.800	1.
6	03:51	00:00:10	n/a	0.054	n/a	n/a	0.800	1.
6	03:52	00:00:11	n/a	0.054	n/a	n/a	0.800	1.
6	03:53	00:00:12	n/a	0.054	n/a	n/a	0.800	1.
6	03:54	00:00:13	n/a	0.054	n/a	n/a	0.800	1.
6	03:55	00:00:14	n/a	0.054	n/a	n/a	0.800	1.

Fig. 10. Modeling Results on Simulation of Rwimi Irrigation Network Operation

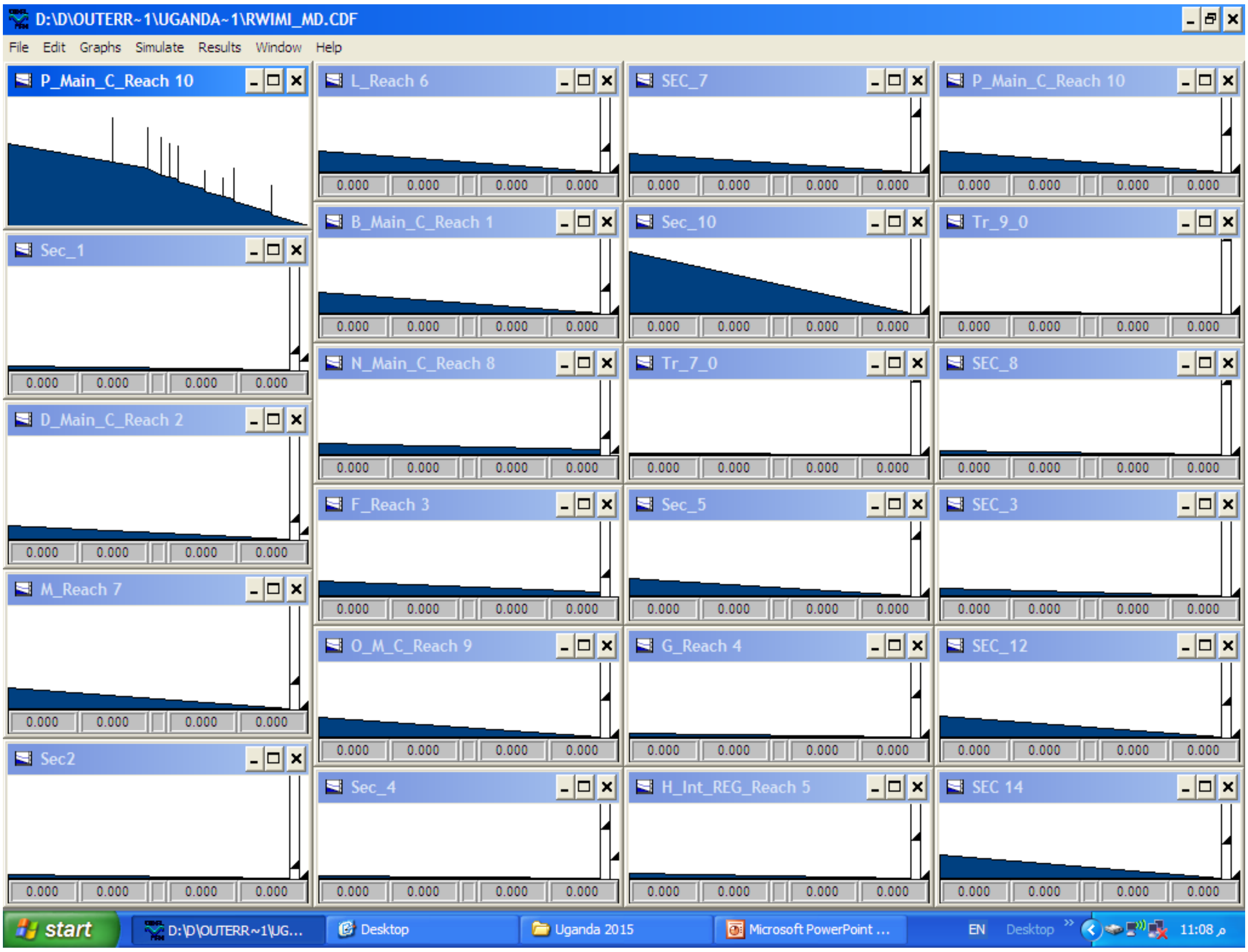


Fig. 11. CANALMAN Simulation Results for "Rwimi" Irrigation Network; Presenting Water Surface, Levels, and Slopes for Feeder Canal and All Branches in Operation

Conclusions of hydrodynamic "CANALMAN" Network Modeling

1. Hydrodynamic model “CanalMan” was effectively used to evaluate the hydraulic behaviors of the proposed irrigation network under operation conditions.

2. A water level was used as an indicator for evaluation of liability and consistency of designed sections and discharges through the defined canal system, and controls (see results figures 11).

3. The performance of canal reaches and regulating structures is meeting the designed objectives, as it satisfied the designed heads and discharges (see figure 10, and 11).

4. The lag-time due to water flow from the intake to various gates and outlets has been computed as shown in the *Operation Table* (fig. 10-***d***).

1- In view of the planned sanctioned demand against specified capacity held by Mains and Minor, its optimal discharge is about 5% less than the design value (8.70 m^3/s).

2- Hydraulic Stability Index (HIS) simulated by the model showed steadiness as it was always ranging between -1.0 and +1.0. (See fig. 11-c).

3- Case Study 3; Network Operation Modeling; Applications of CROP-MATCH model

Most of the irrigation improvement projects were extremely concerning water distribution improvement and water saving throughout physical improvements of the irrigation network (EWAP and IIP projects by MWRI), than concerning development of water distribution strategy. Matching between water demand and availability was mainly concerning the improvement of water managing system and strategy over all the old irrigated lands in Egypt, by the innovated mathematical models' package, which enables flexible, sensitive, and interactive on-demand water supply. Crop-Match was first invented and developed by S. Tony and A. Negm; WMRI (2004), among a package of water managing software; to establish a computerizing water management system for the project of water management enhancement “Matching between Water Demand and Availability”. The model was built based on realistic prediction of water requirements regarding the location, climate, actual cropping pattern, planting time, soil characteristics, irrigation network characteristics, and rotation applied. Crop-Match was founded on cumulative network requirements calculated from tail to head, and was applied in almost all the ARE irrigation districts. The model package enabled the following actions:

- Updating crop-water consumptions over growth stage for all the country’s regions

- Evaluate water requirement at district level (by Crop-Match model).

- Evaluate water requirements at "Directorate level"(by D-Match Model).

- Evaluate water requirements at the Nile basin (by Nile-Demand model).

Model capabilities and constrains: CropMatch is capable to predict water consumptions and requirements for irrigation districts of complex irrigation networks at both: the on-farm and canals levels. More details and features were presented in the literature (S. Tony and A. Negm; 2006, Yousra El Degwee and M. Ashour; 2010, and Ashour, S. El Attar, and Y.El Degwee; 2011).

Model Inputs

The model required two levels of inputs:

a) Permanent Setup and Inputs:

1. District region, location, Names and characters of Irrigation District, Directory, &climatic region

2. Total area served by the district network

3. Dominant Soil Type

4. The main features of the irrigation canals; Canals’ Ranks, Geometry (Length, Bed Width, Side Slopes, Water Depth, Discharge Capacity), and Case of lining (Earth Section, or Lined Canal).

b) Periodical Inputs: all changeable parameters that affect the region water demand:

1. Cropping pattern (every 15 days), and fallow lands.

2. Agriculture, domestic and industrial water requirements, vs. Supplementary Water resources.

3. Updates of irrigation network (Changes, and occasional or seasonal events; i.e. winter closure)

Model Outputs

The model permits wide package of outputs in an interactive manner includes:

- Cropping pattern classification (for the served area), for all canals' ranks
- Water consumption for each crop, at each canal (Distributaries, Branch, and Main Canals)
- Water Requirements for each Canal Level (Distributaries, Branch, and Main Canals)
- Total district water requirements (to be released in main canals)and management categories.

Model Application

a- Calibration and sensitivity: Evaluation of the preliminary results of programs had been conducted, showing high appropriateness and suitability for application with the irrigation network. A slight deviation between the actual and the expected consumptions may not exceed0.8% and preliminary total water saving of 3 ~ 4% is possible due to application of **CropMatch** 1.1.

b- CropMatch Run: Evaluation of "***Tanata Navigation***" canal and its branches is given in fig. 12; where water is diverted to "*El Kased*" canal and "*El Btanuneya*" canal through regulator at km 25.80. The assignment (by WMRI 2011) was to assess the network and to evaluate water requirements of the IIIMP command areas in North Egypt. Water requirements were estimated regarding all the available level and discharge records and measurements. The obtained *CropMatch* results were most reliable when compared with actual consumptions and requirements (see fig. 14).

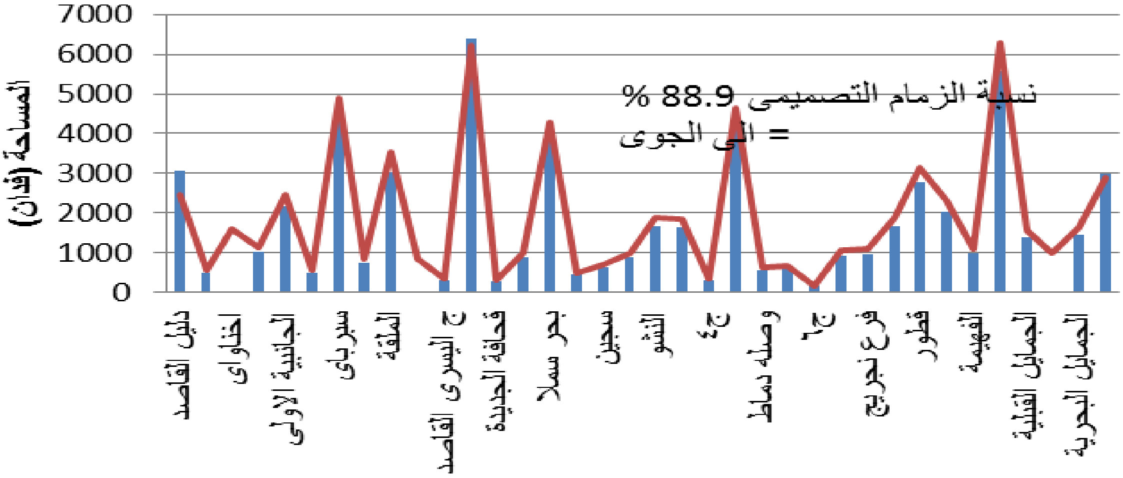


Fig. 12. Actual Served Areas on Tanta Nav. Canal (by branch canal)

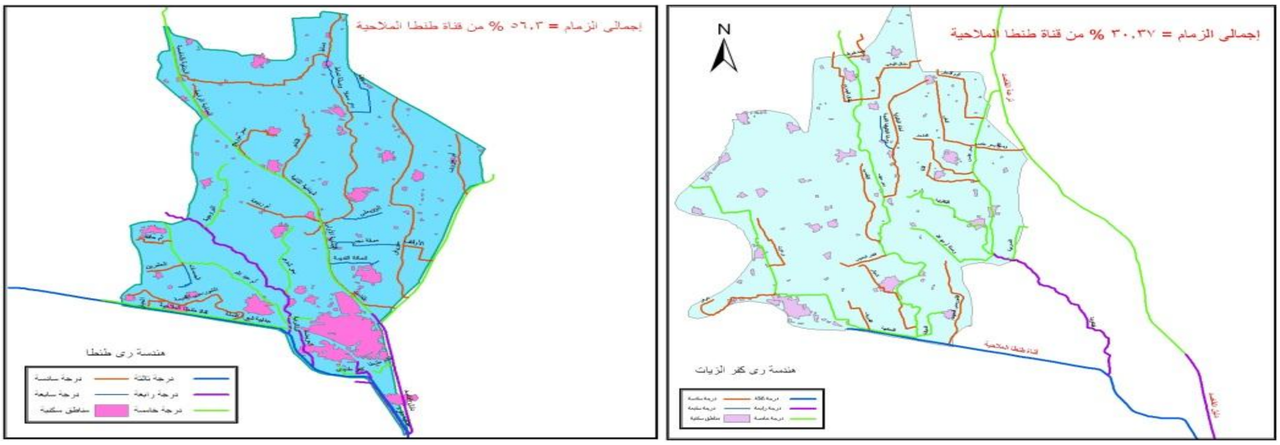


Fig. 13. Tanta Canal Command Area

Tanta canal faced the challenge of the need for increasing its discharge and fears from bank flooding (due to the weak mutual banks with Zenara drains). Modeling revealed that Discharge should be increased (due to the increment of the served area). But however, management scenarios showed need for only slight discharge increment, when irrigation schedules was adopted.

Water Requirements

Water requirements were deduced using the "Crop-Match" model according to cropping pattern scenarios and irrigation alternatives. Results revealed variance of water requirements between 0.6 M m^3/day(in May) to 5.15 M m^3/day(in August) during summer and 0.6 M m^3/day(Oct.) to 1.8 M m^3/day(Feb.) during winter. Also requirements were estimated for *El-Kased* branch during the main consumption seasons according to two different cropping pattern scenarios. Assuming 50% of the served area is "Rice"; the maximum consumption reached 5.15 Mm^3/day for Tanta Canal, while for 70% of the served area is "Rice"; the maximum consumption reached 5.6 Mm^3.

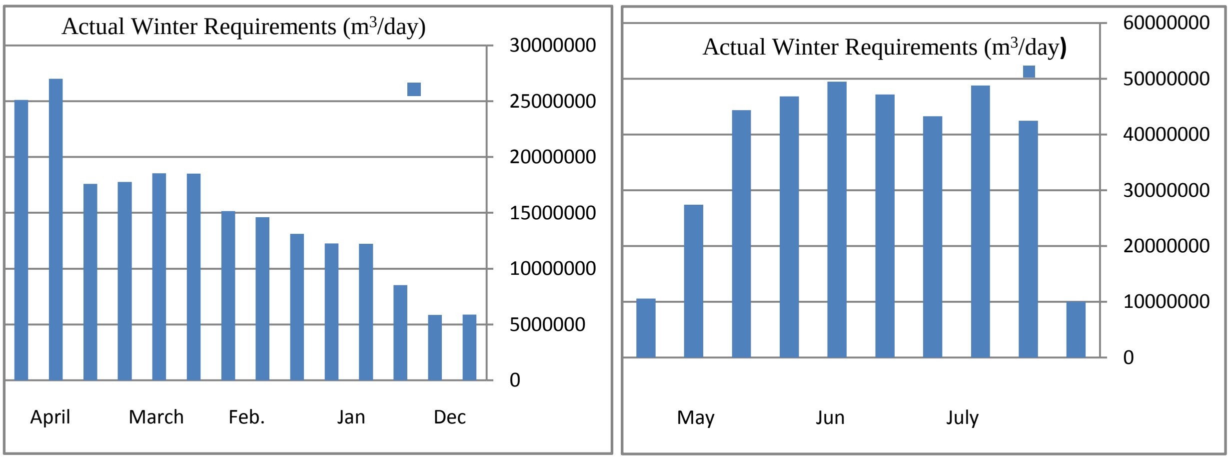


Fig. 14. Crop-Match Results; Seasonal Water Requirements according to Cropping Scenarios

Conclusion of Network Simulation

According to the modeling results; the peak required discharge for the worst scenario of "Tanta Navigation Canal" (70% area; Rice) was 5.15 Mm^3/day, while requirements of "El-Kased Canal" reached 3.2 Mm^3/day. The study also highlighted the importance of water management through controlling on "Btanunia" regulator, while the results of the hydraulic study revealed deficiency in water control and water diversion due to poor management and control. Moreover; modeling revealed a non-homogeneous demand distribution due to concentration of "Rice" areas at the canal end reach. Finally, from studying released discharges; water released is quite sufficient, rather than better management and efficient conveyance will enhance network performance.

4. CONCLUSIONS

This paper focused on reviewing, assessment, and selection of the mathematical modeling in Agro-ecological and water-environmental projects, regarding feasibility, environmental and sustainability visions. The research offers a brief description of modeling concept, and the principles of using models for agro-ecological, on-farm irrigation management, and water productivity. Furthermore, the paper presents a brief evaluation of some commonly used models in water productivity analysis, which was performed under the modeling component activates in Irrigated benchmark project[vi]. Three successive modeling examples by the author were presented: One for applying a tertiary irrigation module developed on *Songwe* River, Tanzania. Another was a Hydraulic (canals) network assessment, in *Rwimi* irrigation scheme, Uganda. The third example concerned evaluation of irrigation network operation on Tanta navigation Canal, Egypt. Generally it was concluded that:

1. Modeling was highly recommended to verify best economic design for agro-irrigation projects enabling adequate farm sizing, channels' and drains' spacing for good irrigation and drainage duties, as well as avoiding relevant problems like deficit irrigation and water logging.

2. For the best modeling and analysis of an agro-ecological system; prior modeling selection and evaluation is worthwhile to permit a lesser modeling complexity; regarding the system boundaries, objectives, and the physical, environmental and financial restrictions.

3. Modeling had supported design of network elements (components) as well as ensured good harmony of operation, efficient performance, and water saving.

4. Modeling enabled examining water managing scenarios (such as applying internal water rotation), system maintenance, helped planning to conserve resources, and permitted maximizing efficiencies of water use and crop productivities.

ACKNOWLEDGEMENTS

Most of this research activity was achieved with association of WMRI team, ICARDA team, and consultant firms like "North Atlantic" (Zambia), CODA (Kenya), and (DCI, and BEC Uganda). The models were available by its original developers and providers like "SALTMED", "Crop-Match", "WP-Calc.", and "Aqua-Crop". Models evaluation and selection criteria was developed in association with ICARDA, as part of "Improving rural Livelihoods through Sustainable Water and Land use Management in Middle East; Up scaling Modeling of Water Benchmark" to determine the impact of water-saving practices on the sustainability of irrigation system, and water productivity (2010- 2013).

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[iii] Case study ICARDA and WMRI; Irrigation Benchmark, 2010

[iv] use continuity and Saint-Venant equations (Strelkoff 1969)

[v] When the Hydraulic Stability Index = zero, the simulated canal system is at equilibrium, and all flow depths and flow rates are constant throughout the system.

[vi] Community-Based Optimization of the Management of Scarce Water Resources in Agriculture in West Asia and North Africa- Phase-II