



**UNIVERSITI PUTRA MALAYSIA**

**MODELING OPTIMAL WATER MANAGEMENT FOR  
RESERVOIR BASED IRRIGATION PROJECTS**

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**MODELING OPTIMAL WATER MANAGEMENT FOR  
RESERVOIR BASED IRRIGATION PROJECTS**

**By**

**MD. HAZRAT ALI**

**Thesis Submitted in Fulfilment of the Requirements for the  
Degree of Doctor of Philosophy in the Faculty of Engineering  
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*Dedicated to the author's heartfelt loving parents and wife*



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## LIST OF ABBREVIATIONS

$A$	Cross-sectional area
$A_r(t)$	Reservoir surface area
$A_v$	Area of void
$A_w(t)$	Watershed area during period $t$
ADAPT	Areal Design and Planning Tool
AGNPS	Agriculture Non-Point Source
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation
ARMA	Autoregressive Moving Average
$B$	Cross-sectional top width
$b$	Soil moisture curve parameter
$BD$	Soil bulk density
BCS	Basin Characteristics System
BGIS	Basin Geographic Information Systems
BRASS	Basin Runoff and Streamflow Simulation
$C$	Percent clay
$c$	Kinematic wave celerity
$C_p$	Specific heat of air at constant pressure
$c_s$	Soil heat capacity
$C_u$	Uniformity coefficient
$C_1$	Constant
$C_2$	Constant
$C_3$	Constant
$C_4$	Constant
CAD	Computer Aided Design
CARL	Central Attributed Raster Line
$CEC$	Ratio of cation-exchange capacity of clay to percent clay
CRSS	Colorado River Simulation System
$D$	Hydraulic depth
$d_s$	Estimated effective soil depth
$\bar{d}$	Mean depth of water stored during irrigation
DHI	Danish Hydraulic Institute
DP	Dynamic Programming
DSS	Decision Support Systems
$E$	Vapor flux rate



$E(t)$	Evaporation rate at the reservoir surface area
$E_c$	Conveyance efficiency
$E_d$	Distribution efficiency
$e_d$	Mean actual vapor pressure of air at dew point temperature
$E_i$	Irrigation efficiency
$E_p$	Free-surface or potential evaporation
$E_u$	Water use efficiency
$e^0$	Saturated vapor pressure of the air
EPAD	Edge Probability Attributed Data
ERDAS	Earth Resources Data Analysis System
ERS	European Remote Sensing Satellite
ET	Evapotranspiration
$ET_a$	Actual evapotranspiration
$ET_p$	Potential evapotranspiration
$ET_p(t, t + \Delta t)$	Evapotranspiration between $t$ and $t + \Delta t$
$F(t)$	Cumulative infiltration
$f$	Infiltration rate
FAP	Flood Action Plan
FARIMA	Fractionally differenced autoregressive integrated moving average
$G$	Soil heat flux
$IG(t)$	Any other gain
GCM	General Circulation Model
GIS	Geographic Information System
GIUS	Geographical Instantaneous Unit Hydrograph
GRASS	Geographic Resources Analysis Support System
$h_c$	Mean height of the crop
$h_0$	Ponding depth
HEC	Hydrologic Engineering Center
HYSSR	Hydro System Seasonal Regulation
$i$	Hydraulic gradient
$I(t, t + \Delta t)$	Infiltration/percolation between $t$ and $t + \Delta t$
$I^j$	Inflow of water diverted from the source to the conveyance system
$IR$	Irrigation requirement
$IR_R$	Amount of water supply from reservoirs
$IR_{Rec}$	Recycled water supply
$IR_{UCF}$	Uncontrolled river flow supply



$K$	Hydraulic conductivity
$K_x$	Lateral hydraulic conductivity of soil
$K_s$	Storage coefficient
$k_s$	Constant
$k'$	Kinematic ratio
$IL(t)$	Any other loss
$L_r$	Leaching requirement
LP	Linear Programming
LHDP	Large-system Hierarchical Dynamic Programming
$M_e$	Effective meteorological input
MADA	Muda Agricultural Development Authority
MWB	Monthly Water Balance
$N$	Possible maximum number of sunshine hours
$n$	Actual number of hours of bright sunshine
NAM	Nedbor Afstromnings Model
NNM	Neural Network Method
NOAA	National Oceanic and Atmospheric Administration
$O_i$	Operational losses
$O_{i,j}$	Overflow in the $i$ th reservoir during the $j$ th month
$OM$	Percent organic matter
$P$	Total deep percolation on the farm
$P(t)$	Precipitation falling on the reservoir surface area
$P(t, t + \Delta t)$	Precipitation between $t$ and $t + \Delta t$
$P_a$	Air pressure
$pD$	Particle density
PRISM	Potomac River Interactive Simulation Model
$Q$	Discharge
$q$	Discharge per unit width
$q_i$	Lateral inflow
$Q_i(t)$	Inflow to the reservoir per unit watershed area during period $t$
$Q^{j+1}$	Water delivered by conveyance system to the field (outflow)
$Q_s(t)$	Uncontrolled releases downstream or spills from the reservoir
$R$	Hydraulic radius
$R(t)$	Required reservoir release rate
$R(t, t + \Delta t)$	Runoff between $t$ and $t + \Delta t$
$R_a$	Extra-terrestrial radiation



$r_a$	Atmospheric vapor resistance
$R_n$	Net radiation
$RH$	Relative humidity
$R_{nl}$	Net long-wave outgoing radiation
$R_s$	Short-wave solar radiation
$r_s$	Vegetation canopy vapor resistance
$S$	Percent sand
$S(t)$	Initial storage volume at the beginning of period $t$
$S_a$	Amount of water supplied to the farm
$S_e$	Energy slope
$s_e$	Effective saturation
$S_f$	Slope of the water surface
$S_I$	Impervious area
$S_I(t + \Delta t)$	Seepage between $t$ and $t + \Delta t$
$S_P$	Pervious area
$S_T$	Total surface area
$S_{i,j}$	Storage of the $i$ th reservoir during the $j$ th month
$S_0$	Bottom slope of the channel
SAA	Snow Accumulation Ablation
SAM	Special Analysis Methodology
SMA	Soil Moisture Accounting
$SP$	Seepage and percolation losses
SSARR	Streamflow Synthesis and Reservoir Regulation
SSG	Synthetic Streamflow Generators
SVAD	Single Value Attributed Data
SWAT	Soil and Water Assessment Tool
SWMP	Surface Water Management Plan
$T_a$	Air temperature
TIN	Triangulated Irregular Networks
$U_2$	Average wind speed at 2m height
USACE	U.S. Army Corps of Engineers
USDAHL	U.S. Department of Agriculture Hydrograph Laboratory
USGS	U.S. Geological Survey
USNWS	United States National Weather Service
$v$	Flow velocity
$v_s$	Seepage velocity



VGFM	Variable Gain Factor Model
$W$	Catchment average amount of soil moisture content
$w$	Elementary area soil moisture at saturation
$W(t)$	Soil moisture content at time $t$
$W(t + \Delta t)$	Soil moisture content at time $t + \Delta t$
$w_i$	Initial moisture content
$W_m$	Catchment average soil moisture content at saturation
$w_m$	Maximum possible soil moisture content
WAM	Weighted Average Method
WAHS	Watershed Hydrology Simulation
WMCS	Water Management and Control Scheme
WUE	Water Use Efficiency
$X$	Weighting factor
$x$	Percentage of pervious area at saturation
$X_i$	Measured value of storage at time $i$
$X_{i+1}$	Generated streamflow
$y$	Average of the absolute values of deviations from the mean
$Y_i$	Measured transformed value of storage at time $i$
$Y_{i+1}$	Transformed generated streamflow
$Y(t)$	Reservoir yield
$z$	Measurement height
$z_0$	Surface roughness height
$\alpha$	Surface albedo
$\Delta$	Gradient of saturation vapor pressure-temperature curve
$\varepsilon_{i+1}$	Random component with mean zero and variance $\sigma_\varepsilon^2$
$\eta$	Porosity of soil
$\gamma$	Psychrometric constant
$\lambda$	Latent heat of vaporization of water
$\mu$	Unit conversion factor
$\mu_x$	Mean of $X$
$\rho_x(1)$	First order serial correlation
$\Psi$	Wetting front soil suction head
$\sigma$	Stefan-Boltzmann constant
$\rho_a$	Air density
$\theta_e$	Effective porosity
$\theta_r$	Residual moisture content

$\Delta S$	Storage increment
$\Delta t$	Time step
$\Delta x$	Distance step
$\Delta \theta$	Change in moisture content
$\nabla_a$	Volume of water applied in an area including rainfall
$\nabla_{nt}$	Net volume of water requirement on day $t$

Abstract of thesis presented to the Senate of the Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

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**October 1999**

**Chairman: Dr. Lee Teang Shui**

**Faculty: Engineering**

The double cropping of rice in the Muda Irrigation Project depends very much on the volume of water stored in the Muda and Pedu reservoirs. The most important problem affecting the project includes constraints related to poor water management. However, the shortage of reservoir water still remains the most severe constraint on the establishment of stable double cropping of rice. Thus, the main purpose of this study is to develop an optimization model and a solution strategy to solve the water resources of the project in a computationally satisfactory manner. In this study, a water balance model was developed and the performance of a project was evaluated. The water balance components were modeled, without incorporating any model calibration parameters. The model results were compared with observed data satisfactorily. The overall project efficiency for the main and off-seasons were also obtained.



A reservoir simulation model was developed and the model storage capacities were compared with the observed storage capacities satisfactorily. The Markov process with periodicity in hydrologic data was applied to generate monthly streamflows. The generated storage capacities were found to simulate with the observed storage capacities satisfactorily. Three different cases of anticipated future monthly storage were envisaged to assess the risk for predicted monthly storage capacities in 1998-2002 and their probabilities of occurrences were computed. An optimization model was also developed to solve the water resources management of a large project in a computationally satisfactory manner. Twelve different scenarios were analyzed to test the performance of the project and their consequences were illustrated. The optimal reservoir storage, optimal irrigation demand, and optimal reservoir release (i.e., optimal reservoir operating policy) were computed. The optimal mean (1987-1997) model total water requirements for the dry and wet seasons were also computed and the optimal contributions by rainfall, reservoir, uncontrolled river flow, and recycled water were determined. The mean water balance components results for different months were stored in GIS data bases, analyzed, and displayed as the monthly crop water requirements maps. Finally, it can be concluded that the integration of the water balance model together with the models for reservoir simulation, efficiency, hydrologic forecasting, optimization, and GIS holds much promise in the analysis of optimal allocation of water resources of a project.





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**PEMODELAN PENGURUSAN AIR OPTIMUM UNTUK PROJEK  
PENGAIRAN BEREMPANGAN**

Oleh

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**October 1999**

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Tanaman padi musim berganda di Projek Pengairan Muda tertakluk kepada isipadu air simpanan didalam empangan Muda dan empangan Pedu. Masalah terpenting mempengaruhi projek termasuk kekangan berkaitan dengan pengurusan air yang kurang memuaskan. Akan tetapi, kekurangan air didalam empangan adalah kekangan terpenting dalam perihal penubuhan setabil tanaman padi musim berganda. Oleh sebab itu, tujuan utama pengajian ini ialah membentuk sebuah model optimum dan strategi penyelesaian demi untuk mengatasi sumber air projek dengan kaedah pengiraan yang memuaskan. Dalam kajian ini, sebuah modelimbangan air telah dimajukan dan prestasi sebuah projek telah dinilai. Modelimbangan air ini boleh menentukan keperluan air tanaman pada sesuatu jangkamasa tentu. Komponen komponenimbangan air dimodelkan, tanpa mengambilkira parameter penentuan. Keputusan keputusan model

