

**OPTIMAL CONJUNCTIVE MANAGEMENT OF GROUNDWATER
AND SURFACE WATER INCORPORATING STREAM-AQUIFER
INTERACTION AND HYDROLOGICAL UNCERTAINTY FOR
SUSTAINABLE DEVELOPMENT AND AGRICULTURAL
PRODUCTIVITY**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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DEPARTMENT OF CIVIL ENGINEERING

Submitted

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CERTIFICATE

This is to certify that the thesis entitled “**Optimal Conjunctive Management of Groundwater and Surface Water Incorporating Stream-Aquifer Interaction and Hydrological Uncertainty for Sustainable Development and Agricultural Productivity**” submitted by **Mr. Mulu Sewinet Kerebih** to Indian Institute of Technology Delhi for the award of **Doctor of Philosophy** is a record of bonafide research work conducted by him. He carried out the work under my supervision for the submission of this thesis, which to the best of my knowledge has reached the required standard.

This Ph.D thesis is original and has not been presented elsewhere for the award of any degree.

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MULU SEWINET KEREBIH

ABSTRACT

The appropriate conjunctive water use management of groundwater and surface water resources draws paramount significance in the backdrop of the ever increasing water demand for agricultural, industrial, and domestic uses particularly in the arid and semi-arid regions as the surface water is very limited and groundwater is already in stressed condition. With this view point, two integrated management models, namely, conjunctive water use simulation-optimization model and optimal land and water resources allocation model were developed. The conjunctive water use simulation-optimization model incorporates the stream-aquifer interaction of the hydrologic process of the physical system prevailing in the basin, managerial constraints that arise due to meeting water demand for irrigation and water supply, environmental flow and water sustainability restrictions and hydrological uncertainty. The optimal resources allocation model involves cropping pattern and seasonal allocation of water resources, rainfall uncertainty and economic return in order to maximize the net agricultural productivity.

A simulation model visual MODFLOW and integrated with GIS was used for the development of conceptual groundwater flow model. Kriging method of interpolation in Arc GIS has been used for spatially visualization and analysis of parameters. The frequency analysis of monthly rainfall data were executed by using normal and log-normal distributions to consider the reliability of rainfall used for irrigation water demand estimation in CROPWAT model. The simulation model was linked with the optimization model internally using response matrix approach for the optimal conjunctive use of surface water and groundwater resources satisfying ecological and drought restrictions and to ensure sustainability of the water resources in the watershed areas. The optimal

solutions of wells were obtained in both the watersheds to investigate the optimal pumping strategies with and without stream flow depletion constraints characterizing environmental flow restrictions.

A groundwater flow simulation model using Visual MODFLOW was first constructed and calibrated to simulate the hydrologic response of the stream-aquifer system in both study areas, namely, Aynalem and Horrat-Golina valley watershed, Ethiopia and it incorporates stream-aquifer interaction and water budgeting of the system. The calibrated model results show good agreement between simulated and observed hydraulic heads in both the watersheds. The sensitivity analyses of calibrated parameters were carried out in both of the watersheds in order to provide reliability and confidence of model results.

The results of optimal pumping indicates that overexploitation of water has been taken place in some of the wells in the Aynalem well field which are mostly located in the lower right bank of the watershed. Groundwater pumping triggers the stream flow depletion in the Aynalem well field and alternative strategic options were evaluated by using the conjunctive management model to moderate the stream flow depletion rates for ecological purpose and to meet demands of the downstream users during dry months. A decrease of optimal pumping rate in the Horrat-Golina valley watershed is observed in some of the wells due to the restriction of stream flow depletion and the optimal conjunctive water use simulation-optimization model has played a great role in preserving groundwater by using surface water when it is sufficiently available. This can reduce the adverse impact of excessive groundwater pumping and can be used in case of deficiency.

The developed resources allocation optimization model was used to determine optimal cropping patterns and water resources allocation at different rainfall probability levels to ensure maximum agricultural production in the Horamat-Golina valley irrigation. The results obtained from optimal cropping pattern shows an increase in net annual return than the government targeted. The findings reveal that the coupled application of simulation-optimization model is very useful to the planners and decision makers in order to ensure sustainable water resources development in the basin.

Further, ANN model has been also developed for the prediction of groundwater level of monitoring wells in the Aynalem well field, Ethiopia. The prediction performance of ANN model was evaluated and a very satisfactory result is achieved. Hence, ANN model has the advantage in the prediction of groundwater level with less intensive data by learning the system behavior of input-output relations simply without the explicit characterization and quantification of the physical system as well as accurate representation of the governing physical laws.

सार

भूजल और सतह के जल संसाधनों के उचित संयोजक जल उपयोग प्रबंधन ने कृषि, औद्योगिक और घरेलू उपयोगों की बढ़ती हुई पानी की मांग की पृष्ठभूमि में विशेष महत्व रखे हैं विशेषकर शुष्क और अर्ध-शुष्क क्षेत्रों में, क्योंकि सतह का पानी बहुत सीमित है और भूजल पहले से ही तनावग्रस्त स्थिति में है इस दृष्टिकोण के साथ, दो एकीकृत प्रबंधन मॉडल, अर्थात्, संयोजन जल का उपयोग सिमुलेशन-अनुकूलन मॉडल और इष्टतम भूमि और जल संसाधन आवंटन मॉडल विकसित किए गए थे। संयुग्मी पानी का उपयोग सिमुलेशन-अनुकूलन मॉडल सिंचाई और पानी की आपूर्ति, पर्यावरण प्रवाह और जल स्थिरता प्रतिबंधों और जल विज्ञान के लिए पानी की मांग को पूरा करने के कारण उठने वाले बेसिन, प्रबंधकीय बाधाओं में प्रचलित भौतिक सिस्टम की हाइड्रोलॉजिक प्रक्रिया की धारा-एक्विडर इंटरैक्शन को शामिल करता है। अनिश्चितता। इष्टतम संसाधन आवंटन मॉडल में फसल का पैटर्न और पानी के संसाधनों के मौसमी आवंटन, वर्षा अनिश्चितता और आर्थिक वापसी शामिल है ताकि शुद्ध कृषि उत्पादकता बढ़ाई जा सके।

एक सिमुलेशन मॉडल विजुअल मॉडफ़्लो और जीआईएस के साथ एकीकृत वैचारिक भूजल प्रवाह मॉडल के विकास के लिए इस्तेमाल किया गया था। आर्क जीआईएस में प्रक्षेप की क्रिगींग विधि का प्रयोग स्तरीय दृश्य और मापदंडों के विश्लेषण के लिए किया गया है। सीआरपीवाट मॉडल में सिंचाई जल मांग के आकलन के लिए इस्तेमाल की जाने वाली वर्षा की विश्वसनीयता पर विचार करने के लिए सामान्य वर्षा के सामान्य वितरणों का उपयोग करके मासिक वर्षा डेटा की आवृत्ति विश्लेषण निष्पादित किया गया। सिमुलेशन मॉडल पारिस्थितिकी और सूखा प्रतिबंधों को संतुष्ट करने और वाटरशेड क्षेत्रों में जल संसाधनों की स्थिरता सुनिश्चित करने के लिए सतह के जल और भूजल संसाधनों के इष्टतम संयोजक उपयोग के लिए प्रतिक्रिया मैट्रिक्स दृष्टिकोण का आंतरिक रूप से अनुकूलन मॉडल से जुड़ा था। पर्यावरण प्रवाह प्रतिबंधों को प्रदर्शित करने वाले प्रवाह प्रवाह की कमी बाधाओं के साथ इष्टतम पंपिंग रणनीतियों की जांच के लिए दोनों वाटरशेड में कुओं का इष्टतम समाधान प्राप्त किया गया था।

दृश्य मोडफ़्लो का उपयोग करते हुए एक भूजल प्रवाह अनुकरण मॉडल का निर्माण पहले ही किया गया था और दोनों अध्ययन क्षेत्रों में, जैसे एनीलेम और होर्मेट-गोलिना घाटी वाटरशेड, इथियोपिया में स्ट्रीम-एक्विफेर सिस्टम के जल-विज्ञान प्रणाली की प्रतिक्रिया को अनुकरण करने के लिए बनाया गया था और यह स्ट्रीम-एक्विफेर इंटरैक्शन और पानी के बजट को शामिल करता है प्रणाली में। कैलिब्रेट किए गए मॉडल के परिणाम दोनों वाटरशेड में सिम्युलेटेड और देखे हुए हाइड्रॉलिक सिर के बीच अच्छा समझौता दिखाते हैं। मॉडल परिणामों के विश्वास और आत्मविश्वास को प्रदान करने के लिए वाटरशेड दोनों में कैलिब्रेटेड मापदंडों का संवेदनशीलता विश्लेषण किया गया था।

इष्टतम पम्पिंग के परिणाम इंगित करता है कि ऐनलैम विद्वान क्षेत्र में कुछ कुओं में पानी के अधिक से अधिक पानी का स्थान लिया गया है जो अधिकतर जल के निचले दायें किनारे पर स्थित हैं। भूजल पम्पिंग एनीलेम क्षेत्र में धारा

प्रवाह की कमी को ट्रिगर करता है और वैकल्पिक रणनीतिक विकल्पों का संयोजन पर्यावरण प्रबंधन मॉडल का उपयोग करके पारिस्थितिक उद्देश्यों के लिए धारा प्रवाह में कमी के स्तर को कम करने और सूखा महीनों के दौरान डाउनस्ट्रीम उपयोगकर्ताओं की मांगों को पूरा करने के लिए मूल्यांकन किया गया था। Horvat-Golina घाटी वाटरशेड में इष्टतम पम्पिंग दर की कमी धारा के प्रवाह में कमी के प्रतिबंध के कारण कुछ कुओं में मनाया जाता है और इष्टतम संयोजनयुक्त पानी का उपयोग सिमुलेशन-अनुकूलन मॉडल ने सतह के पानी का उपयोग करके भूजल के संरक्षण में एक बड़ी भूमिका निभाई है जब यह पर्याप्त रूप से उपलब्ध है यह अत्यधिक भूजल पम्पिंग के प्रतिकूल प्रभाव को कम कर सकता है और इसकी कमी के मामले में इस्तेमाल किया जा सकता है।

विकसित संसाधन आबंटन अनुकूलन मॉडल का उपयोग हिमट-गोलीना घाटी सिंचाई में अधिकतम कृषि उत्पादन को सुनिश्चित करने के लिए विभिन्न वर्षा संभावनाओं के स्तर पर इष्टतम फसल पैटर्न और जल संसाधन आबंटन को निर्धारित करने के लिए किया गया था। इष्टतम फसल पद्धति से प्राप्त परिणामों से सरकार द्वारा लक्ष्य की तुलना में शुद्ध वार्षिक रिटर्न में वृद्धि दिखाई देती है। निष्कर्ष बताते हैं कि बेसिन में टिकाऊ जल संसाधन विकास सुनिश्चित करने के लिए योजनाकारों और निर्णय निर्माताओं के लिए सिमुलेशन-अनुकूलन मॉडल के युग्मित आवेदन बहुत उपयोगी होते हैं।

इसके अलावा, एएनएन मॉडल को एनीलेम वेल फील्ड, इथियोपिया में निगरानी कुओं के भूजल स्तर की भविष्यवाणी के लिए भी विकसित किया गया है। एएनएन मॉडल का पूर्वानुमान प्रदर्शन का मूल्यांकन किया गया और एक बहुत संतोषजनक परिणाम प्राप्त किया गया। इसलिए, एएनएन मॉडल को भूजल स्तर की भविष्यवाणी में लाभ होता है जो इनपुट-आउटपुट संबंधों के तंत्र व्यवहार को सीखकर कम गहन डेटा के साथ लाभ उठाते हैं, बिना स्पष्ट रूप से वर्णित और भौतिक व्यवस्था की मात्रा का ठहराव के साथ-साथ शासी भौतिक कानूनों के सटीक प्रतिनिधित्व भी।

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NOTATIONS

A	Cross sectional area
k_c	Crop coefficient
k_y	Yield response factor
Z	Total water (pumpage from existing wells and diverted from a stream) (L^3)
$(Q_{gw})_{\xi,k}$	Groundwater extraction from cell ξ in time period k (L^3/T)
$(Q_{SD})_{l,k}$	Stream diversion from reach l in time period k (L^3/T)
N_{pw}	Number of groundwater pumping cells
N_R	Number of stream diversion reaches
N_{tp}	Number of time periods in a time horizon.
d_k	Number of days of pumping in the k th month
k	Index for time period
ξ	Index for well number
l	Index for stream diversion site
$s_{\hat{o},n}$	Groundwater head drawdown at cell \hat{o} at the end of period n (L)
$\delta_{\hat{o},\xi,n-k+1}^h$	Drawdown influence coefficient per unit pumping ($L/L^3/T$)
$\beta_{\hat{o},l,n-k+1}^h$	Drawdown influence coefficients per unit flow diversion ($L/L^3/T$)
$(Q_{SD})_{l,k}$	Quantity of water diverted from stream (L^3/T)
$q_{\hat{u},n}^s$	Stream flow depletion rate at reach \hat{u} at the end of time period n (L^3/T)
$\delta_{\hat{u},\xi,n-k+1}^s$	Stream flow depletion influence coefficient per unit pumping ($L/L^3/T$)
$\beta_{\hat{u},l,n-k+1}^s$	Stream flow depletion influence coefficient per unit flow diversion ($L/L^3/T$)

N_{pw}	Number of groundwater pumping cells
N_R	Number of stream diversion reaches.
$(Q_D)_k^{IS}$	Irrigation demand in time period k
$(Q_D)_k^{MS}$	Municipal water supply demand at time period k
$(Q_{gw,lb})_{\xi,k}$	Lower bound of pumping wells
$(Q_{SD,lb})_{l,k}$	Lower bound of stream flow diversions;
$(\bar{Q}_{gw})_{\xi,k}$	Upper bound of pumping wells
$(\bar{Q}_{SD})_{l,k}$	Upper bounds stream flow diversions
Z_p	Net total annual income of crops (Birr, Ethiopia currency)
i	Index for crop season
n	Total number of crops grown in a crop season
P_{ij}	Market price of the jth crop grown in season i (Birr kg ⁻¹)
Y_{ij}	Yield of the jth crop grown in ith season (kg ha ⁻¹)
C_{ij}	Cost of crop cultivation (Birr ha ⁻¹)
a_{ij}	Area allocated to crop j grown in season i (ha)
C_{sw}	Cost of surface water (birr/m ³); C_{gw} = cost of groundwater (Birr/m ³)
$(SW)_i$	Allocation of surface water in season i (m ³)
$(GW)_i$	Allocation of groundwater in season i (m ³)
A_i	Total caltivated command area in season i
GIR_{ij}	Growth irrigation requirement of crop j grown in season i (mm)
E_{sw}	Conveyance efficiency of surface water
E_{gw}	Conveyence efficiency of groundwater

A_j^l	Minimum area under the jth crop
A_j^u	Maximum area under the jth crop
$(Q_{sa})_{l,k}$	Seepage flow between the groundwater flow system and stream reach (L^3/T);
Csb_l	Streambed conductance in stream reach l (L^2/T);
$HS_{l,k}$	Head in stream reach at time k (L);
$h_{i,j,\ell,k}$	Groundwater head in cell i, j, ℓ at time k (L).
K	Hydraulic conductivity of the streambed material in the reach (L/T),
B	Width of the stream reach (L);
L	Length of the stream reach (L),
M	Thickness of the streambed material (L).
ET_c	Crop evapotranspiration
ET	Evapotranspiration
K_c	Crop coefficient,
ET_o	Reference evapotranspiration
R^2	Coefficient of determination
PE_{eff}	Effective rainfall (mm)
P_{tot}	Total rainfall (mm)
R_n	Net radiation at the crop surface ($MJm^{-2} day^{-1}$)
G	Soil heat flux density ($MJm^{-2} day^{-1}$)
T	Mean daily air temperature at 2 m height ($^{\circ}C$)
u_2	Wind speed at 2 m height (ms^{-1})
e_s	Saturation vapour pressure (kpa)
e_a	Actual vapour pressure (kpa)

Δ	Slope vapour pressure curve ($\text{kpa } ^\circ\text{C}^{-1}$)
γ	Psychrometric constant ($\text{kpa } ^\circ\text{C}^{-1}$)
p	Atmospheric pressure (kpa)
λ	Latent heat of vaporization ($2.45 \text{ MJ kg}^{-1} ^\circ\text{C}^{-1}$)
c_p	Specific heat at constant pressure ($1.013 \cdot 10^{-3} \text{ MJ kg}^{-1} ^\circ\text{C}^{-1}$)
ε	Ratio molecular weight of water vapour/dry air = 0.622.
RH	Relative humidity
$(e^\circ(T))$	Saturation vapour pressure at temperature (T)
R_a	Extraterrestrial radiation
G_{sc}	Solar constant = $0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$,
d_r	Inverse relative distance Earth-Sun
ω_s	Sunset hour angle [rad]
$\sin(\delta)$	Solar declination (rad)
R_s	Solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
n	Actual duration of sunshine [hour],
N	Maximum possible duration of sunshine or daylight hours [hour],
a_s	Regression constant
R_{ns}	Net short wave radiation
α	Albedo or canopy reflection coefficient
R_s	The incoming solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
R_{nl}	Net out going long wave radiation
σ	Stefan –Boltzmann ($4.903 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ day}^{-1}$)
u_z	Wind speed at z m height

ABBREVIATIONS

ANN	Artificial Neural Network
AQUACROP	Crop water productivity model
ASCE	America Society of Civil Engineering
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
AWC	Available Soil Moisture Content
AMC	Actual soil moisture content
a.m.s.l	Above Mean Sea Level
BCF	Block-Centered-Flow package
BMC	Billion Metric Cube
CADSM	Command Area Decision Support Model
CDF	Cumulative distribution function
CIA	Central Intelligence Agency
Co-SAERAR	Commission for Sustainable Agricultural and environmental Rehabilitation in Amhara Region
CSA	Central Statistical Agency
CRPSM	Crop Yield and Soil Management Model
DEM	Digital Elevation Model
Dv	Ratio of standard deviation predicted to observed values
EIGS	Ethiopian Institute of Geological Survey
FAO	Food and Agricultural Organization
FNN	Feedforward Neural Network
GA	Genetic Algorithm

GDP	Gross Domestic Product
GIS	Geographic Information System
GOF	Goodness of fit
ISOM	Irrigation Simulation and Optimization Model
ITCZ	Inter tropical convergence zone
KGVDP	Kobo-Girana Valley Development Program
LP	Linear Programming
LNOR	Log normal distribution
MAE	Mean absolute error
ME	Mean error
MCM	Million Metric Cube
MCE	Metaferia Consulting engineering
MoWR	Ministry of Water Resource
MWSSO	Mekelle Water Supply and Service Office
NOR	Normal distribution
NMSA	National Meteorological Service Agency
NSE	Nash-Sutcliffe coefficient error
N-W	North West
PE	Probability Exceedance Level
PDF	Probability Density Function
RIMMOD	Rice Irrigation Management Model
RMSE	Root mean square error

RCH	Recharge
SA	Simulating Annealing
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SMADA	Storm Water Management and Design Aid
STR	Stream
SRTM	Shuttle Radar Topographic Mission
UCA	Unit command area
UN	United Nation
UTM	Universal Transverse Mercator
USGS	United States Geological Survey
USDA	U.S. Department of Agriculture
VES	Vertical Electrical Sounding
WAPCOS	Water and Power Consultancy Services (India) Limited
WGS	World Geodetic System
WWDSE	Water Works, Design and Supervision Enterprise