PN-ACF-139

PROJET

MRT

TADLA RESOURCES
MANAGEMENT

Prepared by
Chemonics International Inc
Resources Management International, Inc
Agricultural Development Consultants, Inc
National Cooperative Business Association
University of California, Davis

Kingdom of Morocco
Ministry of Agriculture and Agricultural Development • Tadla ORMVA
Project financed by USAID • Contract No 608-0213-C-00-4002 • Project No 608-0213-3-20014

PN-ACF-139

Tadla Resources Management Project
Usaid Contract (608-0213-c 00-4002)

A Ground-Water Flow Model for Tadla Plain Morocco

Report No 40

Prepared by

Abdel-Rahman M Shurbaji

July 1996

CONTENTS

Abstract 3

INTRODUCTION 3

PHYSICAL HYDROGEOLOGY 4

MODEL DESIGN 7

- Governing Equation 8
- Model Grid and Boundary Conditions 9
- Hydraulic Properties 12
- Sources and Sinks 12

MODEL EXECUTION 15

- Easy steps to run the model 15
- Visualization of results using ARC/INFO 17

MODEL CALIBRATION 18

- Comparison between simulated and observed water table 18
- Steady-state Calibration 19
- Transient Calibration 22
- Calibration Sensitivity Analysis 22
- Model Verification 22

TIME PLAN **24**

SUMMARY **24**

ACKNOWLEDGMENT **25**

REFERENCES **28**

APPENDIX **29)**

- **Input files** **30)**
- **Output file** **62)**

Figures

1 Map showing model boundary and topography in the study area 6

2 Finite-difference grid for Tadla ground-water flow model 11

3 Map showing the transmissivity field used in the model 14

4 Streams and drains discritized for simulating stream-aquifer relations 16

5 Measured and simulated water-table altitudes 21

A Ground-Water Flow Model for Tadla Plain, Morocco

A R M Shurbaji

Abstract

This report documents the development of a finite-difference numerical model of the ground-water flow system in a 2412 km^2 area of Tadla plain, that includes Tadla Irrigation Perimeter A flow model in the unconfined aquifer is being calibrated for a steady-state condition to determine the hydraulic properties and appropriate boundary conditions for the study area Continuation of this modeling effort is anticipated toward transient calibration so that this model can reliably predict the response of the ground-water system to changes in stresses that affect recharge to or discharge from the system A calibrated flow model will lay the basis for future work related to the modeling of contaminant transport in groundwater, and may be used to evaluate the response of the groundwater system to installing more drains, to a possible drought, or to expansion of irrigated areas Combining the model with an optimization code will form a management tool that can be used to evaluate cost-driven conjunctive use strategies of surface and ground-water resources in the irrigation perimeter

INTRODUCTION

Tadla Plain covers an area of 3600 km^2 to the north of the Atlas Mountain Range, which is about 190 km southeast of Casablanca The Plateau of Phosphates limits Tadla plain from the north In the east, Tadla plain narrows between Atlas Mountains in the south and area of Oued-Zem in the north and northeast To the west is the river, Oued El Abid The southern

boundary of the area is defined by the contact between the deformed rocks of the Middle Atlas Range and the unconsolidated deposits of Tadla Plain The study area in this modeling effort is 2412 km^2 and includes Tadla Irrigation Perimeter which covers 1140 km^2 (Figure 1) The perimeter is divided into two sub-perimeters by the centrally located river, Oum-Er Rbia These sub-perimeters are Beni Amir, 350 km^2 on the right bank of the river and Beni Moussa, 790 km^2 on the left bank

Agricultural productivity in Morocco's Tadla Plain depends on the availability and quality of groundwater which had been conjunctively used with canal water for many years A comprehensive analysis of regional ground-water flow in Tadla irrigation perimeter is essential to the development of solutions to problems that may rise in this area such as the occurrence of shallow ground-water or the occurrence of toxic materials in pumped groundwater As ORMVAT, the agency with responsibility for management of ground-water resources in Tadla irrigation perimeter, is becoming more concerned about nitrate contamination in the aquifer, the need is increasing for a calibrated flow model as a prerequisite for building a ground-water transport model If ORMVAT want to influence the farmers to pump more from groundwater by controlling surface water deliveries or the price for canal water then such a groundwater flow model is needed to study the response of the system to different management strategies This model will always be a main component in any simulation-optimization model used for conjunctive management of surface and ground-waters

The emphasis in this report is on the mathematical approach used in modeling the flow system, the data base on which the model is based, the methods used to calibrate the model, and easy steps to run the model and make use of the results Development of this Tadla Groundwater

Flow Model (Tadla-GWFM) involved both art and science By reading this report thoroughly and the documentation that accompany MODFLOW (McDonald, M G , A W Harbaugh, 1988, Anderson, P F , 1993), one can learn the art of modeling However, a successful modeler should have the basic knowledge in groundwater hydrology in order to practice the art of modeling

PHYSICAL HYDROGEOLOGY

The physical hydrogeology of the study area has been previously described (BRGM, 1993) The study area is underlain by an areally extensive clay layer, which divides the ground-water flow system into two zones an upper unconfined zone and a lower confined zone The base of the unconfined aquifer ranges in depth from 25 to 500 meters

Tadla Plain is mostly gently sloping land with some steeper slopes found in the upper areas northeast in Beni-Amir and Southeast in Beni-Mousa (Figure 1) Average altitude of land surface in the study area is 430 m above mean sea level The climate in Tadla Plain is arid to semiarid The annual pan evaporation of 1800 mm is far in excess of the average annual precipitation of 350 mm/year Rain occurs primarily from November to March Temperature varies seasonally from an average daily minimum of 3 5 °C to an average daily maximum of 38 °C Prior to introducing irrigation in Tadla Plain, recharge to the ground-water flow system was primarily from precipitation and intermittent streams like Oud Ouerna Discharge from the ground-water flow system was primarily by evaporation and discharge to Oum-Er-Rbia river

The present-day hydrology of the area is dominated by agricultural activities Percolation of irrigation water past crop roots and ground-water pumping are the dominant hydraulic stresses on the flow system Most of the ground-water is pumped from the upper unconfined zone Most

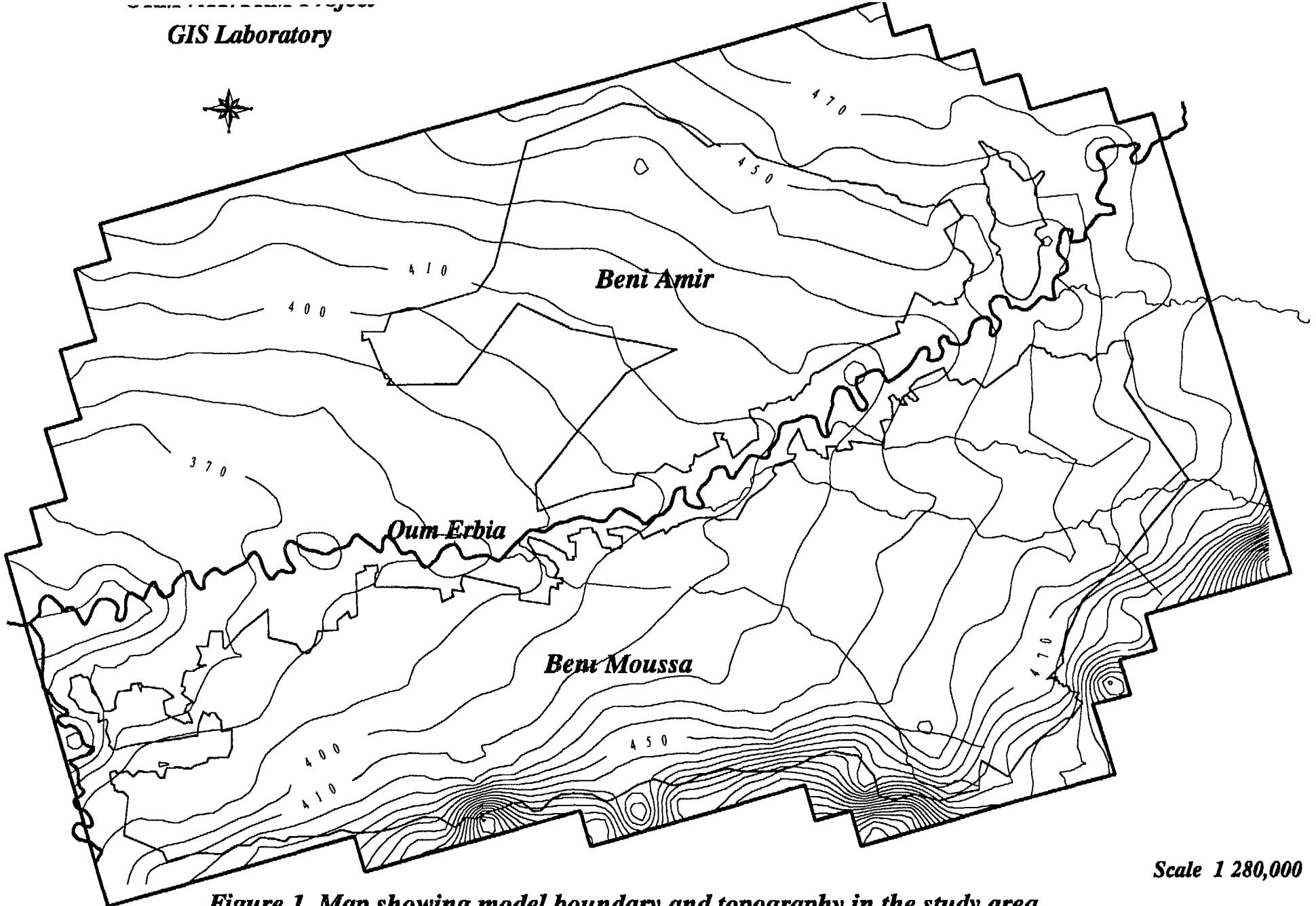

Figure 1. Map showing model boundary and topography in the study area

of the irrigation canal water applied in the Beni-Amir sub-perimeter is derived through a surface canal from a diversion dam on Oum-Er-Rbia river, some 30 km upstream The Beni Moussa sub-perimeter derives its canal water from Bin-El-Ouidane Dam (located on the southern side of the Atlas Mountain) through a 11 km tunnel that penetrates the mountain

Long history of excessive watering of crops using canal water can cause a rise of the water table and evaporation of shallow ground-water and encroaching of ground-water in the root zone can cause increases in soil salinity, further degradation of ground-water quality, and reduced crop yield Salinization has led to the collapse of agricultural economies dependent on irrigation throughout history (Hillel, 1991) Anticipating this problem and in order to control the altitude of the water table, a surface drainage system was installed in the late fifties The average separation distance between the main drains is 5 km and the average depth of these drains is 1 8 m below the ground surface These drains follow the topography in their direction and they discharge in Oum-Er-Rbia river Under normal conditions, these drains carry overland flow following excessive irrigation and heavy rainfall events To meet crop water requirements in the drought years, 1983-1984, many irrigation wells were hand dug and the number of shallow wells to date is approximately 9300 Ground-water pumping is lowering the water table elevation in the area and reduce the potential for shallow water table problems

MODEL DESIGN

A ground-water flow model for the study area was constructed using the U S Geological Survey's three-dimensional, finite difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988) Application of MODFLOW to the flow system requires synthesis of a

large data base and evaluation of several model parameters The accuracy of the model is constrained by the assumptions and simplifications incorporated in the analysis and by the accuracy of the input data

Governing Equation

The governing equation for ground-water flow in the unconfined aquifer is

Equation 1

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + W = S_y\frac{\partial h}{\partial t}$$

where

h=hydraulic head (water table elevation) (L),

T_{xx}= transmissivity in the x direction due to a unit hydraulic gradient in the x direction (L/T),

T_{yy}= transmissivity in the y direction due to a unit hydraulic gradient in the y direction (L/T),

W=external sources of water (T^{-1}),

x,y=cartesian coordinates (L),

S_y=specific yield, and

t= time (T)

This equation is valid for heterogeneous and anisotropic porous medium and it describes a transient system where the system variable, head, changes with time A steady-state condition, where the head is not changing with time, is only an approximation of realty in such a ground-water flow system For the steady-state case, Eqn (1) reduces to

Equation 2

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + W = 0$$

In the simulations undertaken so far, Eqn (2) was solved using the preconditioned conjugate-gradient method for an isotropic case where $T_{xx}=T_{yy}$ in every cell

Model Grid and Boundary Conditions

Areally, the study area was discritized using a 22 row by 33 column grid, with each model cell 2 km on a side (Figure 2) The southern boundary of the grid approximates the contact between the Atlas Mountain Range and the unconsolidated alluvium The Atlas range acts as a ground-water barrier and is treated in the model as a no-flow boundary The western boundaries of the grid approximate flow lines and are treated as no-flow boundaries The study area is hydraulically connected to other areas in the north and east and the boundaries were determined to be specified-head boundaries Across these specified-head boundaries, the flux into (or out of) a given cell is controlled by a conductance term and the head difference across the boundary

Equation 3

$$Q = C(H_b - h_{i,j})$$

where

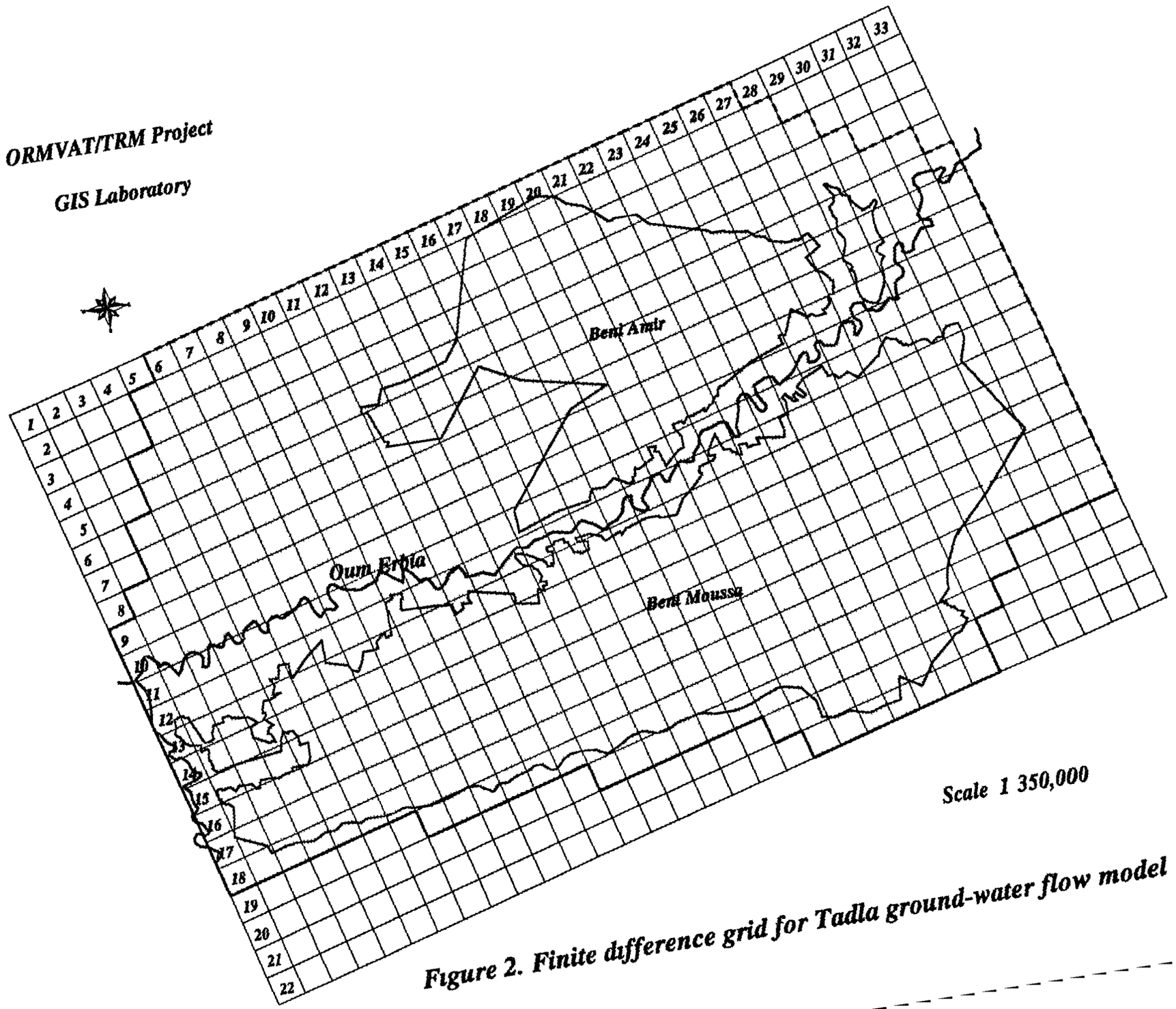

Figure 2. Finite difference grid for Tadla ground-water flow model

Q=flow rate between a cell and the boundary (L^3/t),

C=conductance across the boundary (L^2/t),

H_b=head at the boundary (L), and

$h_{i,j}$=head in model cell (row i and column j) adjacent to the boundary (L)

Hydraulic Properties

Within the aquifer, transmissivity data (obtained from pumping tests) is available at several locations in the area (DRH, 1972) These transmissivity values have an average value of $6\ 76\times10^{3}$ m/s For logarithmic transmissivity, the average value and standard deviation were -2 17 m^2/s and 0 70, respectively Values that are separated more than 2 2 times the standard deviation were believed to be wrong and were removed from the data set Transmissivity values for all cells in the model grid were calculated using kriging interpolation on logarithmic transmissivity An exponential semivariogram model was found suitable for the logarithmic transmissivity data Figure 3 shows the generated transmissivity field, as well as location of points of transmissivity measurements (pumping wells) used in kriging

Sources and Sinks

Within the domain of the model, the sources and sinks are recharge, ground-water pumping, leakage between the aquifer and drains and streams, inflow and outflow from boundaries and evaporation Recharge and pumping in the model are spatially distributed The rate of applied water derived from canal water is 1 0 m/year and the rainfall rate is 0 35 m/year Irrigation efficiency is believed to be 27% which means recharge from irrigation is 0 27 m/year

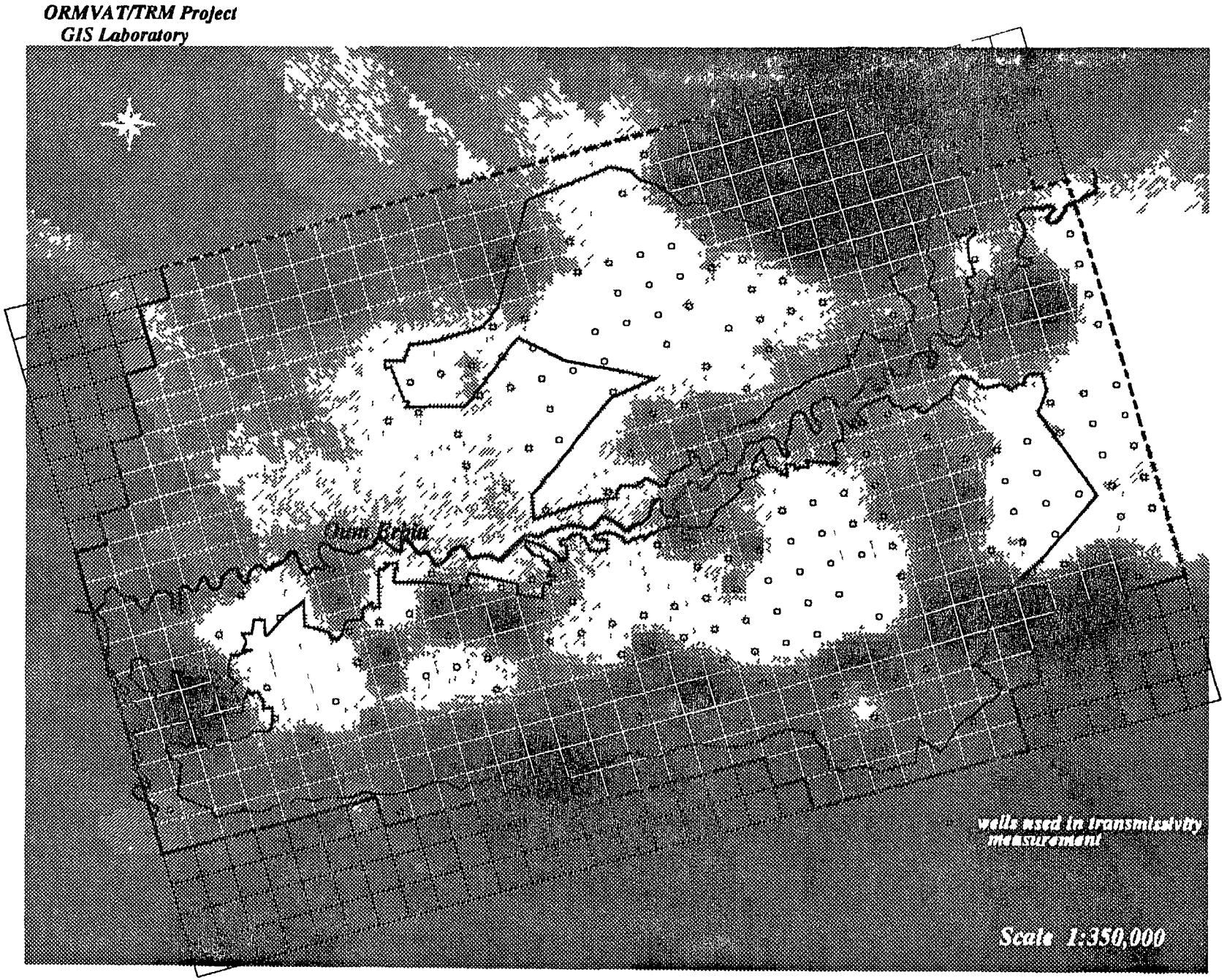

Figure 3. Map showing the transmissivity field used in the model

Infiltration efficiency from rainfall is believed to be 24% leading to 0 08 m/year reaching ground-water

The model uses the river package in MODFLOW to simulate leakage between the ground-water system and streams and drains that interact with ground-water Streams and drains superimposed on the model grid are divided into segments and reaches (Figure 4) A segment is a stream or drain in which streamflow from surface sources are added at the beginning of the segment A reach is the part of a segment that corresponds to an individual cell in the grid The model uses piecewise linear head-dependent function to represent flow between a reach (or reaches) and the corresponding cell in the aquifer Consequently, reach bottom altitude and conductance need to be specified for each model cell containing a drain or a stream The conductance for each reach was calculated as a function of the length of that reach in the cell The model also uses peicewise linear head-dependent functions to represent evaporation The extinction depth used is 2 3m and a value of 0 35m was used as the maximum evaporation rate from the ground-water (if located at ground surface), which is equal to the maximum recharge rate (Belitz and Phillips, 1995)

MODEL EXECUTION

Easy steps to run the model

To run the model, the user should access the directory (e g , c \tadla\modtadla\gwmodel) that contains the input files (e g , run2 bas, bcf, wel) and the executable file (modflow exe) from In WINDOWS, clicking on the icon of the execution batch file (e g , run2 bat) will start the simulation, and in few seconds the output file (e g , run2 out) will be generated Examining the

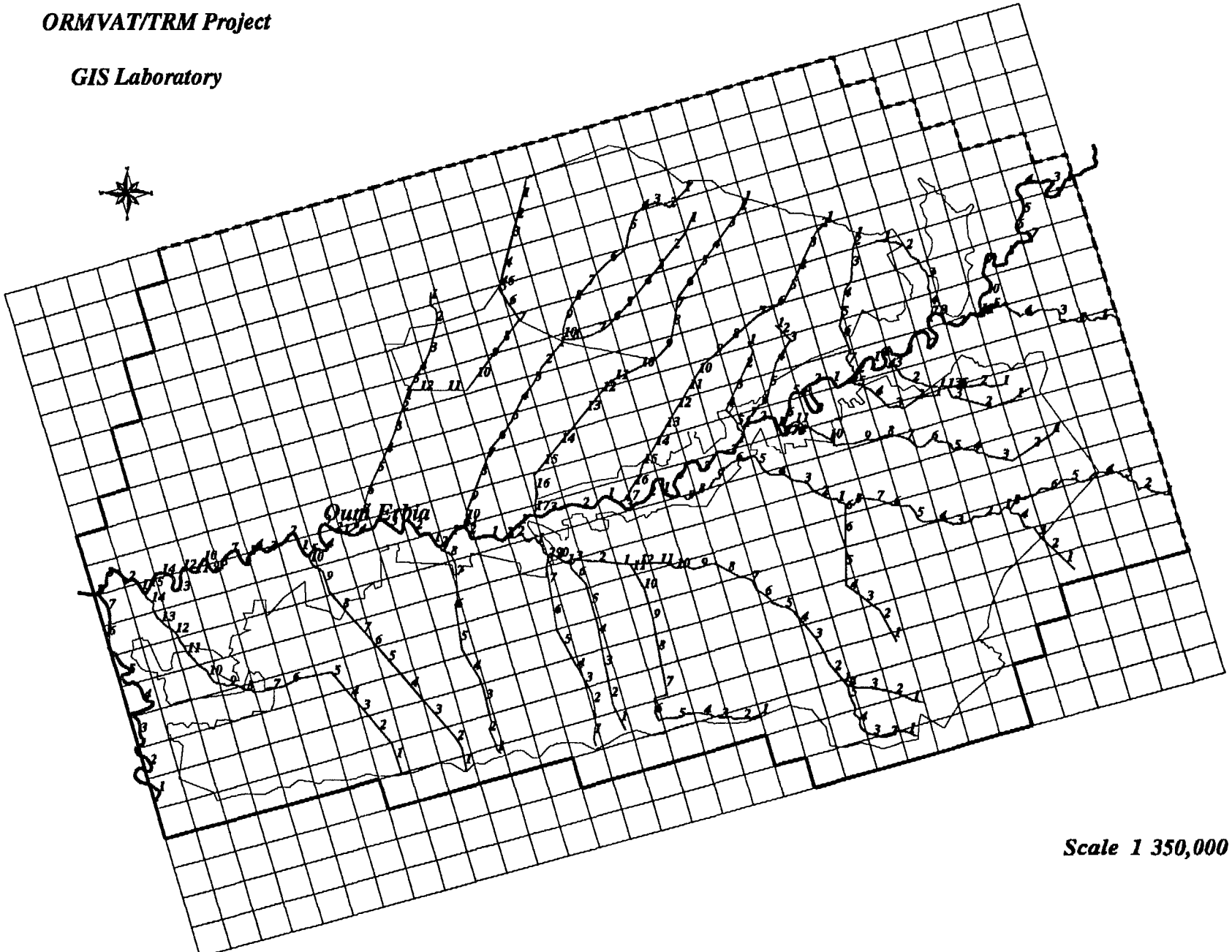

Figure 4. Streams and drains discritized for simulating stream-aquifer relations

results given in the output file is the right thing to do before plotting heads The content of the batch file, input files, and the output file are given in the appendix

To generate a file (e g , head2 dat) having the format x y, head (where x y are the coordinate distance along columns and rows for the center point of a cell) , the user is expected to run postmod exe and input the binary file (e g , head30 bin) generated by MODFLOW However, the head data file needs some processing before it can be moved to the UNIX station, on a diskette, for input to ARC/INFO, a Geographic Information System (GIS) software For the grid (see Figure 2), each cell is given an identification number (ID) that relates to its location in the grid (row, column) Using a spread sheet program (e g , Excel), the same IDs for cells are given to the corresponding records in the head data file The records for inactive cells should be removed from this file The number of active cells in this model is 603 cells (see Figure 2) The ID corresponds to the node (center) of the cell and also it corresponds to the cell itself Using the ID one can find for each node the model x,y coordinates and the GIS real coordinates Input to ARC/INFO should be in real x,y coordinates The data is transferred to ARC/INFO either in text delimited file or dbase file with the ID given to each record The head values will be given to the points representing the cell centers and can be stored in an item in the point coverage generated for these points or a new coverage can be generated from the text file Contours will be generated for simulated heads from the values given for all active cells and for the case of observed head, interpolation is needed first to estimate values for the nodes in active cells

Visualization of results using ARC/INFO

Visualization water table contours on a map that shows the model boundary the transmissivity values, and also the monitoring wells used to generate the measured water elevation contours well help evaluate the choice of boundary conditions Plotting these heads on a map with the river and drains is also very valuable to understand the function of the river and drains Visualization using ARC/INFO has no substitute in personal computer applications In this modeling study, ARC/INFO was also a design and an analysis tool, it was used to generate the model grid, perform interpolation to calculate observed head values for the center of each grid cell, and transmissivity values for each cell, and generate contours for simulated and measured heads and for topography

MODEL CALIBRATION

The purpose of calibration is to establish that the model can reproduce field-measured heads and flows During calibration a set of values for aquifer parameters and stresses is found that approximates field-measured heads and flows Calibration is done by trial and error adjustment of parameters or by using an automated parameter estimation code

Comparison between simulated and observed water table

In this study a head-constrained calibration approach was taken, simulated water levels were compared to obseved water levels for the 100 monitoring wells The location of these wells is given in Figure 5 In fact, simulated and measured heads are compared for the centers of the 92 cells containing the 100 monitoring wells, where observed water levels in the centers of these cells were determined using interpolation Comparison between simulated and observed

water levels (heads) was evaluated using two statistical measures, the root mean square error and the bias which are defined as follows

Equation 4

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{[h_{mea}(i) - h_{sim}(i)]^2}{n}}$$

Equation 5

$$BIAS = \sum_{i=1}^{n} [h_{meas}(i) - h_{sim}(i)]$$

where

RMSE= root mean square error,

n= number of measurements,

h_{meas}= measured head,

h_{sim}= simulated head, and

i= summation index

The root mean square error is a relative measure of the error associated with the difference between simulated and measured heads Positive or negative differences in head have equal effects on the calculations System-wide tendencies toward positive or negative head differences are reflected in the bias value

Steady-state calibration

Figure 5 illustrates the measured water-table elevation in October 1995 and the simulated water-table elevation from an initial run The reader may refer to input files (given in the appendix) to know the values of parameters used in the simulation The poor correspondence

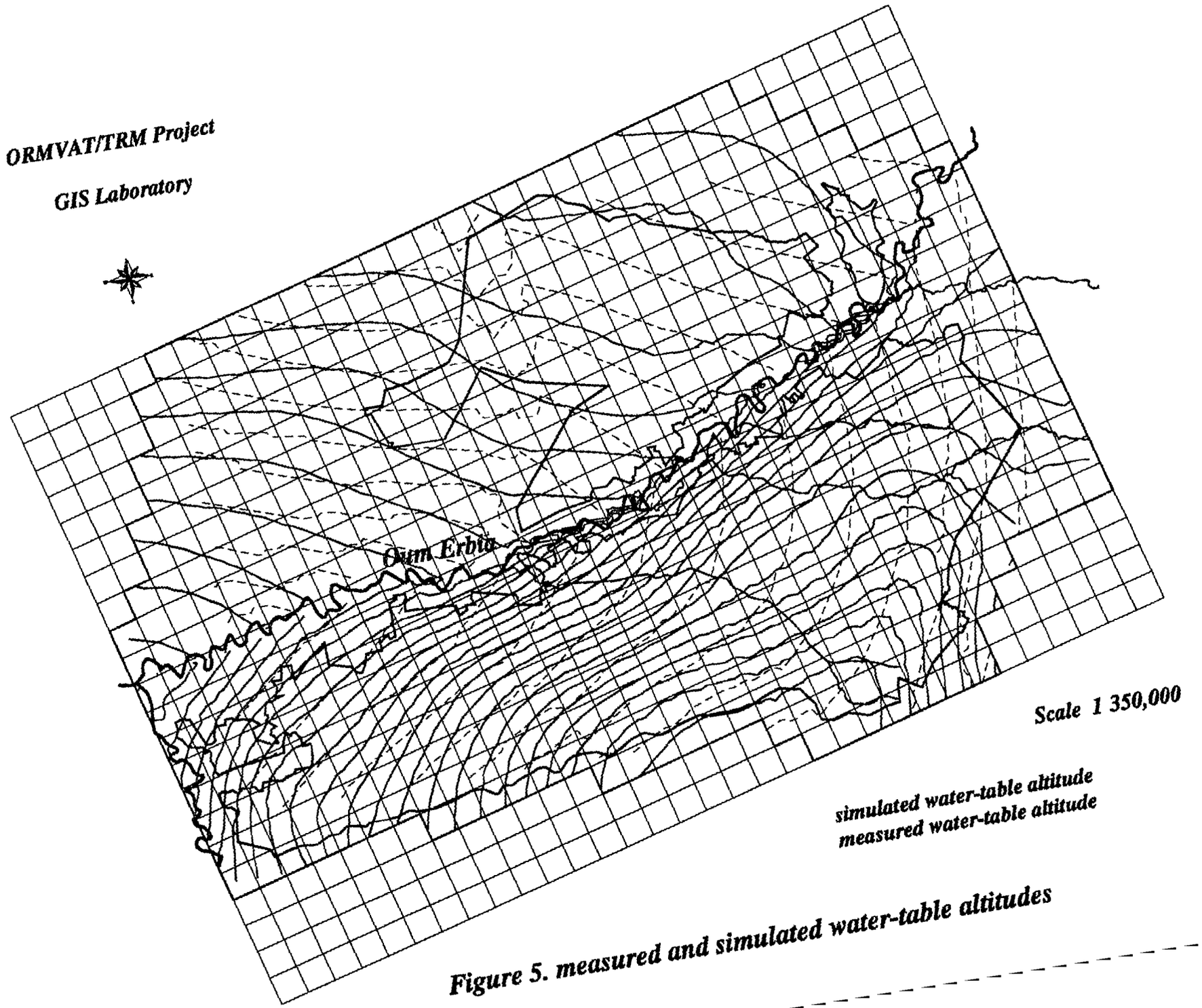

Figure 5. measured and simulated water-table altitudes

between simulated and measured contours suggests the need for more calibration runs Obviously, the boundary condition in the bottom east corner need to be changed from no flow boundary to specified-head boundary In subsequent runs, the conductance per meter for the river bottom, the anisotropy ratio, the average transmissivity, and values along specified-head boundaries will be taken as the calibration parameters

Transient Calibration

In the calibration effort under transient conditions, specific yield and conductance terms for drains will be treated as calibration parameters The sensitivity of the model to changes in the calibrated parameters identified in the steady-state condition should be determined again and values should be selected so that the model perform well in both cases For transient simulation, the initial distribution of heads in the system also is needed

Calibration Sensitivity Analysis

The calibrated model is influenced by uncertainty owing to the inability to define the exact spatial (and temporal) distribution of parameter values in the model domain A sensitivity analysis is needed in order to establish the effect of uncertainty on the calibrated model

Model Verification

To establish greater confidence in the model, at least two more sets of measured water levels should be examined and compared to the simulated condition using the set of calibrated parameter values

APPLICATIONS

The development of this model is expensive (in terms of labor time, the computer resources used, and the extensive field information required for input data) However, applications can only be meaningful if the model is calibrated This model will be utilized whenever professionals in ORMVAT want to make informed analysis or prediction about the consequences of a proposed action that will affect recharge to or discharge from the ground-water system

The flow model, once calibrated, can be utilized (1) in defining flow path lines which are also path lines for contaminant transport in the aquifer, (2) for building a contaminant transport model, (3) in the evaluation of the ground-water system response to (a) installing more drains, (b) a possible drought, (c) expansion of irrigation to include some rainfed areas, and (4) to evaluate cost-driven conjunctive management of surface and ground-water resources in the irrigation perimeter

This modeling effort is taking advantage of the GIS laboratory, which will be continuously utilized to accomplish the goals of this study, having a verified ground-water flow model Any future modeling effort will also use the same procedures for data transfer between personal computers and UNIX station Once the model is calibrated it can be moved to the UNIX station

TIME PLAN

Activity	Weeks needed
Calibration under steady state condition	3
Sensitivity analysis	1
Transient calibration	3
Report writing	2
Training (I) using the model	1
(II) Applications	1
(II) Advanced modeling skills	2

SUMMARY

A numerical model was developed for the regional ground-water flow system in 2412 km^2 of Tadla Plain, that includes Tadla irrigation perimeter The model is currently being calibrated under steady-state condition by comparison to water levels observed in October 1995 Two more data sets are needed for the steady-state calibration procedure This modeling effort is not complete and only after achieving calibration under steady-state and transient conditions, it can used with confidence in making predictions This report (manual) documents all the steps undertaken in the modeling process (1) understanding the physical hydrogeology and building a conceptual model for the ground-water flow system, (2) model design which includes the mathematical formulation (governing equation), grid orientation and design, data requirements

based on the grid, governing equation, sources/sinks, and boundary conditions, and (3) building the input files, running then model and visualizing the results, and (4) model calibration

Acknowledgment

I gratefully acknowledge the support provided by the staff of the Tadla Resource Management [TRM] Project (E Rawson, R Gaddis, and M Khatouri) and the Office Regional de Mise en Valeur Agricole du Tadla [ORMVAT] (M Laaroussi and M El Boustani) throughout the development of this ground-water model

I am also indebted to the many people who made it possible for me to complete this important phase of the study M Benhida worked with me hand in hand in field investigations, data collection and management, and preparation of data files to MODFLOW and ARC/INFO A Bellouti and M Farhi took a leading role in GIS activities and figure preparation M Vayssieres provided ideas for interpolation and contouring using ARC/INFO M Mellak collected water levels from monitoring wells and obtained land surface altitude from topography maps T Elmostafa helped in computer data entry M Foweteh assisted in area measurements The author also acknowledge M Kettani for report editing and translation from English to French

The work was financially supported by the United States Agency for International Development (AID project No 608-0213-C-00-4002)

team work makes a difference

REFERENCES

Andersen, P F , 1993 A manual of instructional problems for the USGS MODFLOW model International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado

Andersen, M P and W W Woessner, 1992 Applied groundwater modeling Simulation of flow and advective transport Academic Press, San Diago, CA 92101, U S A

Belitz, K and S P Phillips, 1995 Alternative to agricultural drains in California's San Joaquin Valley Results of a regional-scale hydrogeologic approach Water Resources Research, 31(8) 1945-1862

BRGM, 1993 Etude du systeme aquifère multicouche de la plaine de Tadla

DRH (Regional hydraulic division), 1972 Perimetre d'Irrigation du Tadla Caracteristiques hydrauliques de la nappe phreatique

Hillel, D , 1991 Out of the Earth Civilization and the Life of the Soil, 321 pp , Free Press, New York

McDonald, M G , A W Harbaugh, 1988 A modular three-dimensional finite-diffeence ground-water flow model, in Techniques of Water Resources Investigations of the United States Geological Survey, Book 6, Cap A1, U S Geol Surv , Washington, D C

Debbarh, A , 1994 Etude Environmentale du Perimetre du Tadla Gestion Quantitative et Qualitative des Resources en Eau et Sol des Perimetres irrigues de Beni Mousa et Beni-Amir, MRT Project, USAID, Morocco