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DRAINAGE IN THE LBOD PROJECT OPERATIONAL CONCERNS AND QUALITY OF PUMPED EFFLUENT

By

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I. ABSTRACT

The Left Bank Outfall Drain (LBOD) Stage-I Project, implemented in the Sindh Province in the Lower Indus Basin during 1985 to 1997 at a cost of over Rs. 27 billion, is the biggest drainage project in Pakistan. The project aimed at the provision and rehabilitation of a variety of drainage and irrigation infrastructures for adequate maintenance of the root zone environment for optimum cropping and yield in an area of about 577,000 hectares. The project area is situated in the commands of the Rohri and Nara Canals that off-take from the Sukkur Barrage. For Project implementation purpose, the command area has been divided into the Nawabshah, Sanghar, and Mirpurkhas components. Due to favorable hydrogeological conditions in the LBOD-Nawabshah component project area, the provision of large capacity drainage tubewells has been made for subsurface drainage to alleviate waterlogging and salinity conditions in the root zone.

This study is aimed at developing a three-dimensional hydrodynamic groundwater model for the LBOD-Nawabshah area and evaluating the present and future management of drainage tubewells in order to reduce the drainable surplus. The sensitivity analysis for the area to the net recharge is also included in the study. The developed LBOD-Nawabshah groundwater model is a valuable tool to identify the critical areas with a water table within the danger limit of 1.5 m. The proposed management strategy of operating tubewells at their full capacity in critical areas only, show up to 30 percent saving in highly saline drainable surplus when compared to the operation of all tubewells at full capacity. The proposed strategy, when compared to the current operation of drainage tubewells, shows a significant reduction in the extent of the critical areas. Also, the LBOD-Nawabshah model has shown a high sensitivity to the net recharge in the area.

II. INTRODUCTION

The province of Sindh lies in the southeast of Pakistan with an area spanning 14.06 million hectares. The fertile Indus plain in the Sindh Province (Figure 1) has alluvial deposits ranging several hundred meters between the Kirthar Range and the Thar Desert, and is known as Lower Indus Region/Basin (LIR). The region has been a natural attraction for agricultural activities in the area for centuries. The climate in the region is hot and arid. In order to harness the full benefits and needs of agro-climatic conditions, three barrages (Sukkur-1932, Kotri-1955, and Guddu-1962) were built on the Indus River, that command more than 5.456 million hectares under assured irrigation supplies. However, the lack of drainage infrastructure in a flat terrain irrigation basin and the long-term accumulation of irrigation losses have resulted in a high water table in the region causing waterlogging, salinization, and storm water flooding.

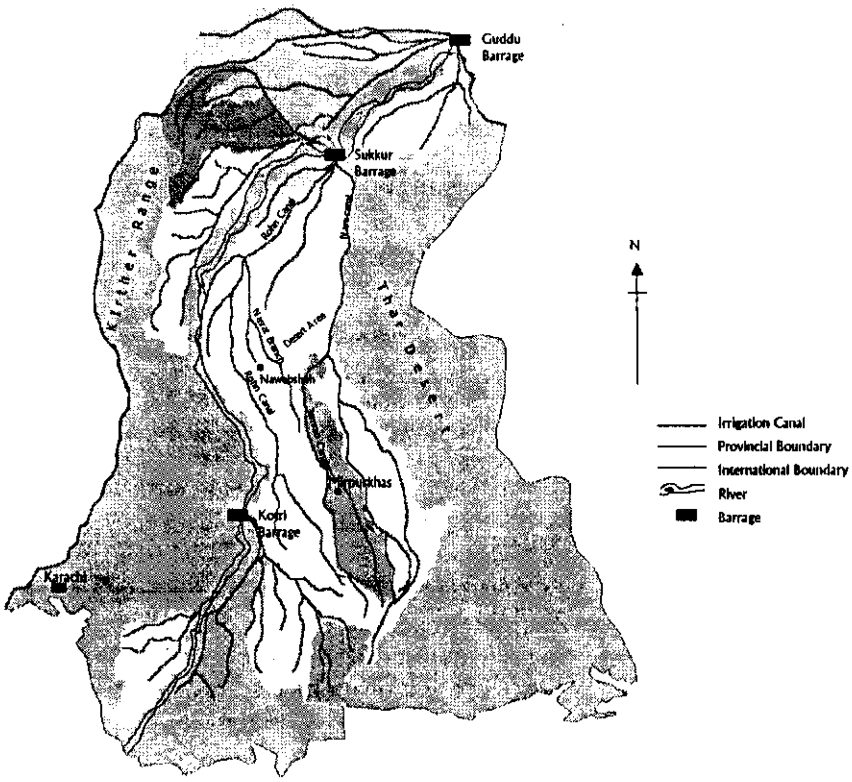


Figure 1. The Lower Indus Region.

During the mid 1960s, the Water and Power Development Authority (WAPDA), Government of Pakistan, launched a project study known as the Lower Indus Project (LIP) in the commands of the Guddu, Sukkur and Kotri Barrages. The project aimed at the preparation of a plan for the optimal development of the water and land resources of the LIR lands with concurrent control of waterlogging and salinity. The study was entrusted to Hunting Technical Services Ltd./Sir M. Macdonald & Partners (HTS/MMP) to carry out extensive investigations in the fields of agriculture, irrigation, and drainage. A comprehensive plan for the agricultural development of the LIR was formulated in the form of the Lower Indus Report published in 1965, based on the analysis of basic data gathered in the region.

One of the major waterlogging and salinity control projects proposed in the Lower Indus Report (HTS/MMP, 1965) was the construction of the Left Bank Outfall Drain (LBOD) and its component projects. The project envisaged serving an area of about 2 million hectares in the perennially irrigated command area of the Sukkur Barrage on the left bank of the Indus River. Phase-I of the LBOD project, initiated in 1974, included the part construction of a spinal drain and storm water drainage to serve a catchment of 0.73 million hectares. In 1980, the then British Overseas Development Administration (ODA) sponsored a study on the development of the LBOD beyond Phase-I. The study report proposed a 20-year program of surface and sub-surface drainage in a catchment of about two million hectares. The study divided the program into ten component project areas, including the three priority areas of Nawabshah, Sanghar, and Mirpurkhas for first stage implementation. However, the proposal was delayed due to financial constraints and some other prerequisite studies. In the meantime, the Government of Pakistan funded a core program to complete works on the spinal and outfall drains.

The LBOD Stage-I Project for the integrated development of irrigation and drainage in the three priority areas (covering 0.577 million hectares) was started in 1985. The drainage works of the project constitute the largest drainage program in Asia for exporting the drainable surplus resulting from subsurface drainage, storm water drainage, and canal escapes to the Arabian Sea for disposal. A variety of drainage technologies consisting of tubewells, tile and interceptor drains, surface drain network, spinal drain, outfall drains, and a tidal link has been provided in the project area. The irrigation works comprise the construction of the Chotiari Reservoir (by enlarging the existing storage arrangements east of the lower Nara Canal), remodeling of the Nara and Jamrao Canal systems, construction of canal escapes, and implementation of the on-farm water management program (WAPDA, 1996). A large part of the Stage-I project has been completed and the remaining works have been dovetailed into the newly launched National Drainage Program.

A. OPERATION AND MAINTENANCE ISSUES

The public sector is unable to cope with and sustain operation and maintenance of various developments that have taken place in the country under the current institutional arrangements, and the agriculture sector is no exception. The real benefits of a project like the LBOD can not be achieved if the developments are not properly and judiciously utilized. Under the National Drainage Program, institutional reforms in the fields of irrigation and drainage are being experimented/implemented by involving communities at the grass root level for operation and maintenance of irrigation and drainage infrastructures. Fortunately, the advancement in science and technology has made it possible to simulate the cause and effect relationship of various activities in a system and to plan and prepare economical, efficient and optimum strategies for management purposes in a timely manner. The operation and maintenance of installed drainage tubewells under the LBOD Stage-I Project is the single-most expensive activity to maintain the water table at a desirable depth for optimum cropping and yield. These tubewells discharge mostly saline groudwater, except areas comprising small fresh water pockets and lenses along canals in the Nawabshah and Sanghar Component Projects. The preparation of a management plan for the operation of these tubewells requires conceptualization of the groundwater system, understanding of the water bearing media, inflow and outflow patterns, and extensive monitoring of the water table fluctuations.

Mathematical models have been found to be a practical aid in arriving at a reasonable understanding of the physical regime that they represent. Modeling involves an approximation of the field conditions in a physical or mathematical way for a particular purpose (Anderson and Woessner, 1992). A mathematical model employs mathematical equations and procedures to represent a system, and can be solved analytically or numerically. A groundwater flow model depicts the appearance of actual aquifer by means of governing equations describing the physical processes active in the aquifer/groundwater system (Mercer and Faust, 1980a). A groundwater model is useful to predict the consequences of a course of action, understanding the regional flow system dynamics, assembling and organizing the field data, and formulating the regional regulatory guidelines for a specific region (Anderson and Woessener, 1992). A typical modeling process is depicted in the flow chart shown in Figure 2.

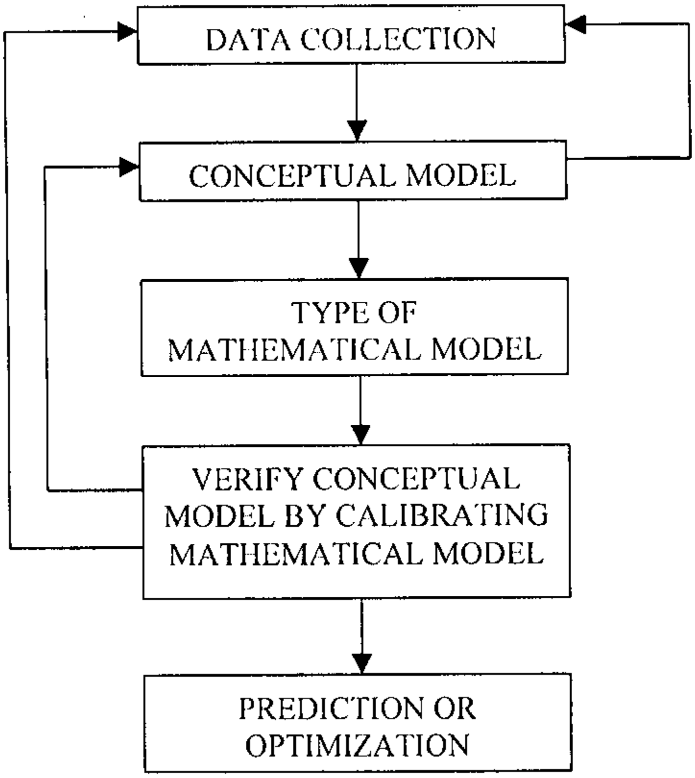


Figure 2. A Typical Mathematical Modeling Process.

B. OBJECTIVES

This study is aimed at developing a three-dimensional hydrodynamic groundwater model for the LBOD-Nawabshah Component Project area and involves calibration of the model to observed conditions, and predicting the groundwater levels resulting from the operation of installed tubewells. The objective of the study is to prepare a management plan for tubewells in order to maintain an adequate root zone environment for optimum cropping and yield.The management strategies for the operation of the tubewell drainage system are compared in terms of the amount of drainable surplus and extent of the area retaining watertable within 1.5 m depth, termed as critical area.

C. AREA

Administratively, the LBOD-Nawabshah Component project area comes under the jurisdiction of the Naushahro Feroze, Nawabshah, and Sanghar Districts of the Sukkur and Hyderabad

Divisions. Geographically, the area lies between latitude 68° 5′ and 68° 45′ N and longitude 25° 53′ and 26° 45′ E (Figure 3). The real coordinates can be referenced to the Survey of Pakistan metric coordinate system gridded datum for Pak Zone 2A. The datum has been projected against the Lambert Conformal Conic Projection and corresponds to the Northing displacement from 912,000 m to 1,004,000 m and Easting displacement from 2,160,000 m to 2,220,000 m for the area. The component project area, covering a gross area of 253,338 hectares and a culturable command area of 224,403 hectares, is located in the perennial commands of the Rohri Main Canal along the western boundary and the Jamrao Canal on the eastern boundary. The area draws daily irrigation supplies of more than six million cubic meters through an elevated network of branch canals, distributaries, minors and watercourses.

D. PHYSIOGRAPHY AND GEOLOGY

The terrain in the project area is generally flat, with the land sloping 0.014% (14 cm/km) southeastwards away from the Indus River. The area is dominated by meander and cover flood plains and some relief is provided by the channel remnants and bar deposits left by the old course of the river towards the west (WAPDA, 1996). The northeastern part has aeolian desert fringes constituting the boundary of the irrigation area. The alluvial deposits by the Indus River in the area consist of fine to medium micaceous sands interbedded with silt and clay in a limited areal extent. These deposits are of pleistocene age and recent epochs over a basement of tertiary rock (WAPDA, 1996). The groundwater in the area is saline (EC 10-40 dS/m) in most of the command area, except some fresh water pockets and lenses along major canals (MMP/HTS, 1984). This constitutes an extensive alluvial saline aquifer with a good hydraulic connection to the water table under the area i.e. unconfined aquifer. The area is suitable for provision of subsurface drainage to control the rising water table by installing tubewells (HTS/MMP, 1965 and WAPDA, 1996).

E. CLIMATE

The climate in the component project area is hot and arid. May and June are the hottest months with an average maximum temperature of about 44°C. The coldest month is January with an average minimum temperature of about 7°C (SMO, 1997). The average annual rainfall is about 150 mm, of which more than 80 percent falls in the monsoon months of July and August. The area is sometimes subject to severe storms, which cause serious flooding in the absence of well-defined natural drainage and the presence of irrigation and road embankments. The average open water evaporation varies from 10.9 mm/d in summer to 2.5 mm/d in winter (MMP/HTS, 1984). The area lies in the wheat-cotton belt with sugarcane, oilseed and orchards being the other major crops. The annual cropping intensity is about 120 percent (WAPDA, 1996).

F. DRAINAGE DEVELOPMENT UNDER THE LBOD STAGE-I PROJECT

Drainage infrastructure development under the LBOD Stage-I project in the Nawabshah Component is comprised of both surface and subsurface drainage systems. The control of the water table and leaching/reclamation of salt-affected soil in the culturable command area is facilitated by the provisions of a subsurface drainage system consisting of 465 tubewells (276 conventional wells and 189 scavenger wells) and 154 km of horizontal interceptor drains along with sumps and disposal channels. A 600 km-long surface drainage network of main, branch, and sub-drains, along with appurtenant cross drainage structures and storm water inlets is provided to convey subsurface drainage effluent and storm water runoff to the spinal drain.

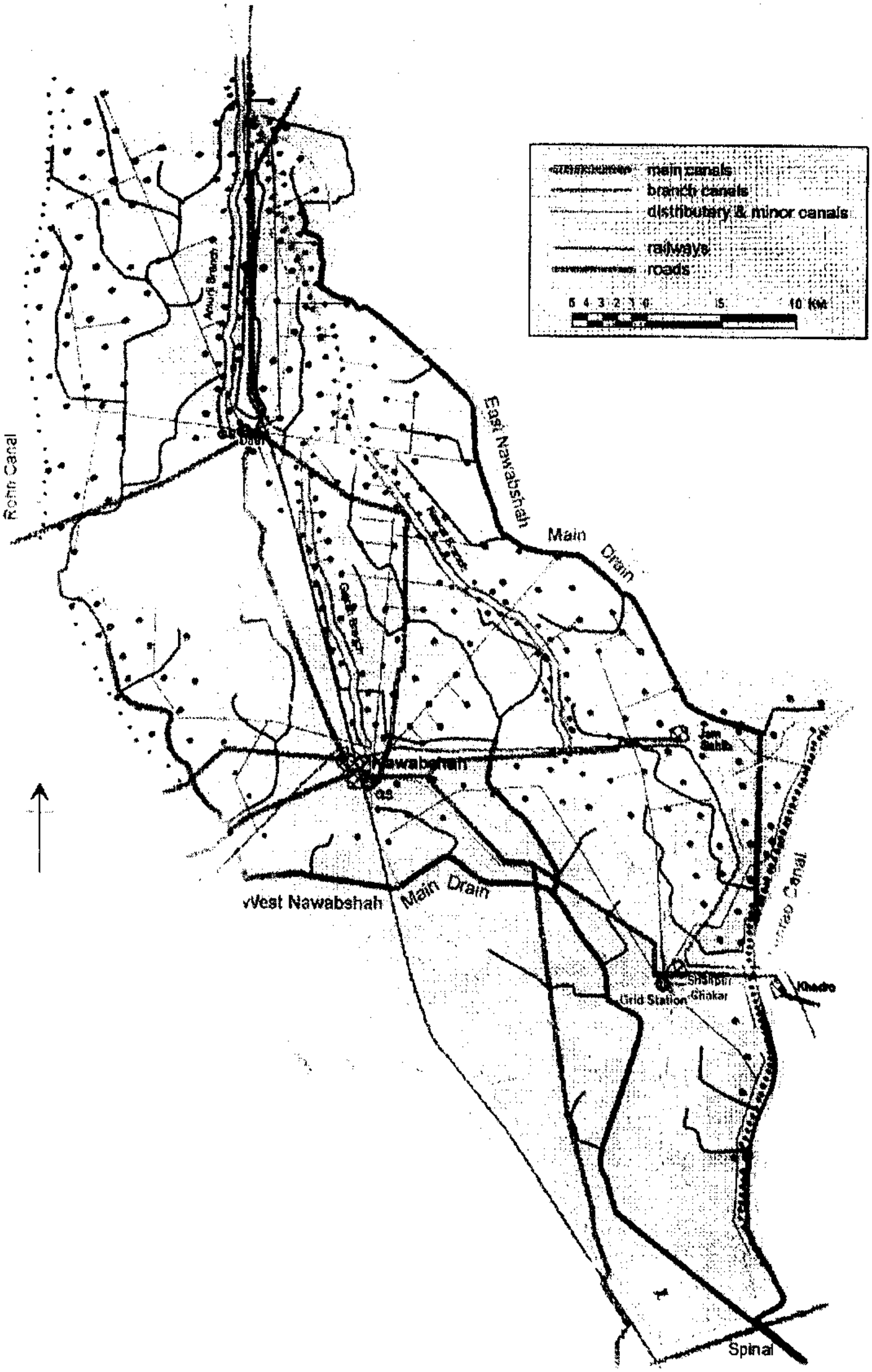


Figure 3. The LBOD-Nawabshah Component Project Area.

G. WATER BALANCE

The water balance for the LBOD-Nawabshah area has been conceptualized to consist of irrigation water supplies and rainfall to the area, evapotranspiration and pumping of drainable surplus out of the area, and changes in storage of soil moisture and groundwater. The groundwater sub-system inflows considered are conveyance losses from main and branch canals, and net recharge. The net recharge is considered as areal flux to groundwater resulting from conveyance losses from the distributaries, minors and watercourses, application losses on the field, rainfall contribution, unaccounted groundwater extractions, and return flow from pumped water. The outflows from the sub-system are capillary upflow or direct loss from the water table and pumping. The base flow, or down valley flow, in such a flat terrain basin is considered negligible.

III. MODEL DEVELOPMENT

The development of the LBOD-Nawabshah groundwater model (GWM) is followed by an overview of similar related work in LIR and the selection of a system of standard code for groundwater flow simulation. This consists of: selecting the model domain; designing the grid mesh; characterizing the aquifer; fixing simulation time, stress period and time step; setting up initial and boundary conditions; specifying aquifer parameters (hydraulic conductivity and specific yield); and preparing Well, River, Recharge, and Evapotranspiration Packages. The International System of units (SI) is adopted in this modeling effort, with simulation time unit of day.

The Sindh Irrigation and Power Department implemented a pilot project, the "Second SCARP Transition North Rohri Pilot Project (SSTNRPP)" (ACE et al.,1997) situated between the Rohri Main Canal and the Indus River on the western side of the LBOD-Nawabshah Component project area. Under the project, hydrogeological and groundwater model development studies were carried out to simulate the hydrodynamics of groundwater flow (using MODFLOW) and solute transport (using MT3D) to model the switch over from deep pumping wells to relatively shallow pumping wells.

The aquifer is characterized as a single layer unconfined aquifer, but for modeling purpose is divided into three layers in accordance with the average depths of various tubewells. The groundwater quality in the project area is characterized as usable that degrades with depth. Well, River, Recharge, and Evapotranspiration Packages modelled the various stresses on the aquifer, and contained the elements of water balance for the groundwater subsystem.

The study concluded that the shallow pumping from newly installed private and community tubewells at the existing and higher pumping rates would not cause adverse effects in a large part of the project area. Deep pumping through original SCARP tubewells and seepage wells would result in the formation of larger poor quality groundwater zones.

One of the recommended modeling protocols is the selection of a computer program that contains the verified governing equations representing the physical processes occurring in porous media and the verified code generating the solution for the mathematical model comprised of governing equations (Anderson and Woessener, 1992). Processing MODFLOW for Windows (PMWIN) provides a complete simulation system for modeling groundwater flow, solute transport, particle tracking, and parameter estimation processes using the following codes (Chiang and Kinzelbach, 1996):

1. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model-MODFLOW of the United States Geological Survey;
2. A Modular Three-Dimensional Transport Model-MT3D;
3. Particle Tracking with PMPATH for Windows or MODPATH; and
4. Parameter Estimation Program-PEST.

Only MODFLOW capabilities of PMWIN are utilized and discussed in this report.

A. MODFLOW

MODFLOW is the most popular and widely used public-domain groundwater flow simulation model. The code is written in FORTRAN language and structured into a main program and a series of independent subroutines grouped as a module/package to deal with specific features of the hydrologic system (C Vision, 1997). The code solves the block-centered finite difference approximation of the partial differential equation combined with specified initial and boundary conditions. The hydrodynamic equation, describing the three-dimensional movement of incompressible groundwater through a porous material, is as follows (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y \frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z \frac{\partial h}{\partial z}\right] - W = S_s \frac{\partial h}{\partial t}$$

Where K_x, K_y, and K_z are hydraulic conductivity values along x, y, and z directions, respectively [LT^{-1}], h is piezometric head [L], W is volumetric flux per unit volume representing sources/sinks of water [T^{-1}], S_s is specific storage of the porous material [L^{-1}], and t is time [T].

The capabilities of MODFLOW include simulation processes representing types of layers as confined, unconfined, and/or a combination of the two; external stresses, such as wells (Well Package), streams (River Packages), drains (Drain Package), areal recharge (Recharge Package), and areal loss from the water table (Evapotranspiration Package); and boundary conditions of specified head, specified flux, and head dependent flux (General Head Boundary Package). The finite difference solution methods provided are iterative Strongly Implicit Procedure (SIP) and Slice-Successive Over Relaxation (SOR). The flexibility and modularity of the MODFLOW program encouraged adding relevant new packages. PMWIN includes some new stress and solver packages such as stream flow routing, reservoir, preconditioned conjugate gradient 2 (PCG2) solver, etc. The processes are represented in the form of independent packages allowing the examination of the effects of various stresses, one by one. For LBOD Nawabshah GWM, stress packages used are Well, River Recharge and Evapotranspiration while newly added PCG2 solver package is utilized for numerical solutions.

1) Model Domain

The elevated main and branch canals in the area provide conditions of hydrologic divides and recharging boundaries for modeling purposes. For the LBOD-Nawabshah Component project area, the Rohri Main Canal on the west and the Jamrao Canal on the east fulfil such conditions. To avail similar conditions, the modeled area is extended to the head regulator of the Nasrat Branch in the north and to the tail of the Jam Branch system in the south. The Nasrat Branch, previously an inundation canal, is now the biggest branch canal system on the Rohri Main Canal, and provides irrigation water to most of the component project area. The northeast of the component project area is bordered by the Thar Desert. Thus, the selected domain approximately forms a hydrologically closed basin for modeling purposes.

2) Grid Layout

The selected model domain is replaced by a discretized domain, which consists of a grid of uniform block-centered finite difference square cells of 2,000 m for numerical modeling purposes. The grid is drawn on the area map with the lower left corner having Easting of 2,160,000 m and Northing of 900,000 m, while the upper right corner Easting and Northing are 2,230,000 m and 1,044,000 m, respectively (Figure 4). Therefore, the discretized domain has 72 rows numbered from north to south (top to bottom) and 35 columns numbered from west to east (left to right), for a total of 2520 grid cells. The location of a cell is represented in terms of the column (j), row (i), and layer (k). A no-flow boundary is constituted automatically around the model domain, within which cells are designated as active and inactive. An inactive cell is impermeable, or constant head, i.e. where the head is not computed or fixed during simulation. For the selected domain, 1030 cells are designated as active cells, where heads can vary dynamically.

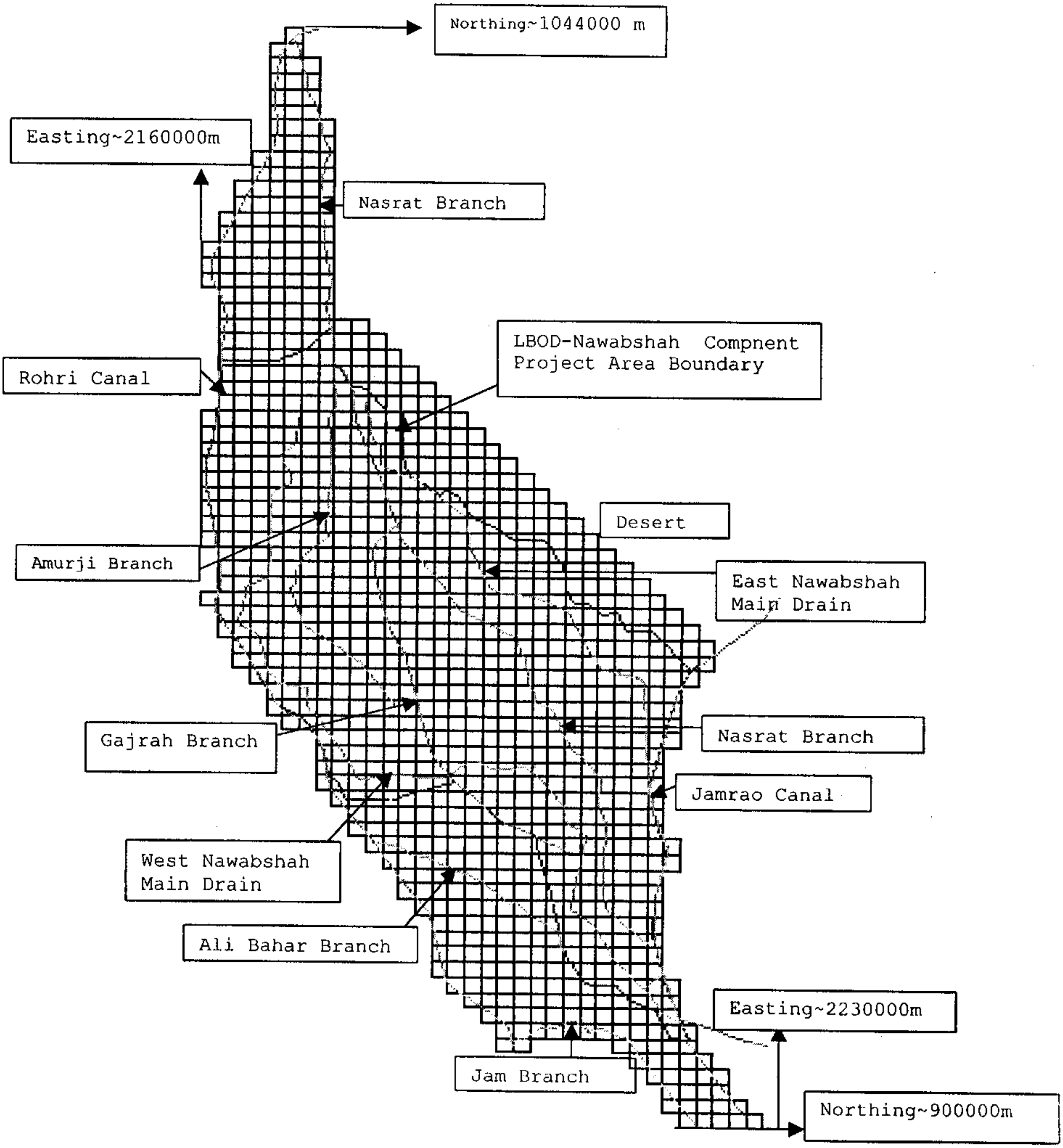


Figure 4. The LBOD-Nawabshah GWM Finite Difference Grid.

3) Aquifer Characterization

The LIP study (HTS/MMP, 1965) characterized the Lower Indus alluvium as a huge, highly transmissive, unconfined saline aquifer of more than 180 m deep. The LBOD-Nawabshah GWM is considered part of this large and contiguous groundwater reservoir, with a good hydraulic connection to the water table and the streams/irrigation canals. The natural surface levels above mean sea level in the model area vary from 36 m in the northwest to 17 m in the southeast. The bottom of the aquifer is considered up to an elevation of 160 m below mean sea level for this modeling study.

4) Simulation Time

The simulation time is divided into the calibration period and prediction period. The calibration period is from May 1988 to April 1998, covering pre- and post- LBOD Stage-I Project developments. The prediction period targets April 2010. Each period is further divided into stress periods and time steps.

The stress period in MODFLOW considers uniform stresses (e.g., pumping or recharge) during a period of time from the user's point of view. The stress period for the LBOD-Nawabshah GWM is in accordance with the cropping seasons of Kharif and Rabi and the annual field measurements of the water table in April and October by the SCARPs Monitoring Organization (SMO), WAPDA. The Kharif stress period is considered from May 1 — October 31 consisting of 184 days, and Rabi from November 1 — April 30 for 181 or 182 days, depending upon the leap year.

The time step in MODFLOW further divides the stress period into intervals during which the head is computed from the solver's point of view. Higher calculation accuracy is attained when the number of time steps are increased in a stress period, but with a longer duration of calculations. The number of days in each stress period constitutes the number of time steps for the stress period. The simulation time unit is day.

5) Initial and Boundary Conditions

The gridded water levels from 253 field observation locations of April 1988 (SMO, 1997) served as the initial head distribution for the model under consideration. The cells, representing portions of the Rohri Main Canal and the Jamrao Canal, a segment of the Nasrat Branch Canal in the north and the Jam Branch system, constituted the hydrologic divides and recharging boundaries for the study area. These are modeled as river cells. The cells, bordering desert in the northeast and small irrigation areas in the north and south ends, are modeled as constant flux boundary cells.

6) Aquifer Parameters

Hydrogeological investigations in the component project area were part of the LIP study (HTS/MMP, 1965). Details of exploratory boreholes and test production wells constructed during the study are available. These are supplemented with additional lithological logs of boreholes drilled during the LBOD Stage-I Project preparation (MMP/HTS, 1984) and bore logs of tubewell construction details of the LBOD-Nawabshah. These provided the basis for specifying aquifer parameters (hydraulic conductivity and specific yield values for unconfined aquifer) for the model area and further refinement under the calibration process. The aquifer test results on nine production wells conducted under the LIP study (HTS/MMP, 1965), along with their digitized locations, are summarized below in Table 1.

Table 1. Aquifer Parameters for Selected Tubewells in LBOD-Nawabshah GWM.

Tubewell Number	Easting (m)	Northing (m)	Hydraulic Conductivity (m/d)	Specific Yield (%)	
				Aquifer Test	Laboratory
RN-05	2169008	1025715	22.6	-	-
RN-08	2167391	1005381	35.1	25	-
RN-10	2177092	1010927	28.5	35	25.1~25.3
RN-11	2177092	994289	26.4	40	-
RN-12	2175475	972106	41.9	4.5	15.1~41.1
RN-15	2177092	948075	42.6	3	12.8~23.8
RN-16	2198111	962863	24.6	6	15.1~39.2
RN-18	2202961	929589	19.8	17	18.9~44.6
RN-19	2212662	959166	27.5	7	17.9~40.6

Source: Supplement 6.1.3, 4, and 5, Volume 6, Lower Indus Report (HTS/MMP, 1965).

The laboratory tests for specific yields were conducted on the samples collected from the upper stratum of the well boreholes. The gridded values of these test results are specified in the model, subject to change during the calibration process.

7) Stress Packages

The stress packages conceptualized for the LBOD-Nawabshah GWM are Well, River, Recharge, and Evapotranspiration. The justification and procedure of preparation of each package are described in the following subsections.

▸ Well Package

There are 276 conventional drainage and 189 scavenger tubewells installed in the LBOD-Nawabshah Component project area. The Operation and Maintenance Directorate (OMD) of WAPDA (South), established in 1995 on the directives of the then Prime Minister of Pakistan, looks after the needs of O&M of drainage facilities, including tubewells for the LBOD Stage-I Project. These tubewells have been functional since Kharif 1995. The directorate, *interalia*, maintains a monthly record of the actual discharge, hour-meter readings, energy-meter readings, and maintenance needs of every tubewell. The locations of most tubewells have been recorded by the SMO (1997) using the Global Positioning System (GPS) instrument, and the remainder are digitized. The tubewells are categorized into East Nawabshah, West Nawabshah and scavenger tubewells. The features of these tubewells, along with their locations, are given in Annexure-I, Table A.

Preparation for the Well Package involved the following steps:

1 To identify the cell location of a tubewell, termed as pumping cell on the model grid, post maps of tubewells showing Northing-Easting locations, symbols and labels are prepared using SURFER for Windows (Golden Software Inc., 1996) and imposed over the model grid. The pumping cell row and column numbers are noted for identification purposes.

2 465 tubewells of the LBOD-Nawabshah Component project are grouped into 269 pumping cells over the model grid (Figure 5).

3 The maximum possible discharge rate (Max Q) for the pumping cell is estimated using the installed capacity and designed operating factor of 14 hours per day.

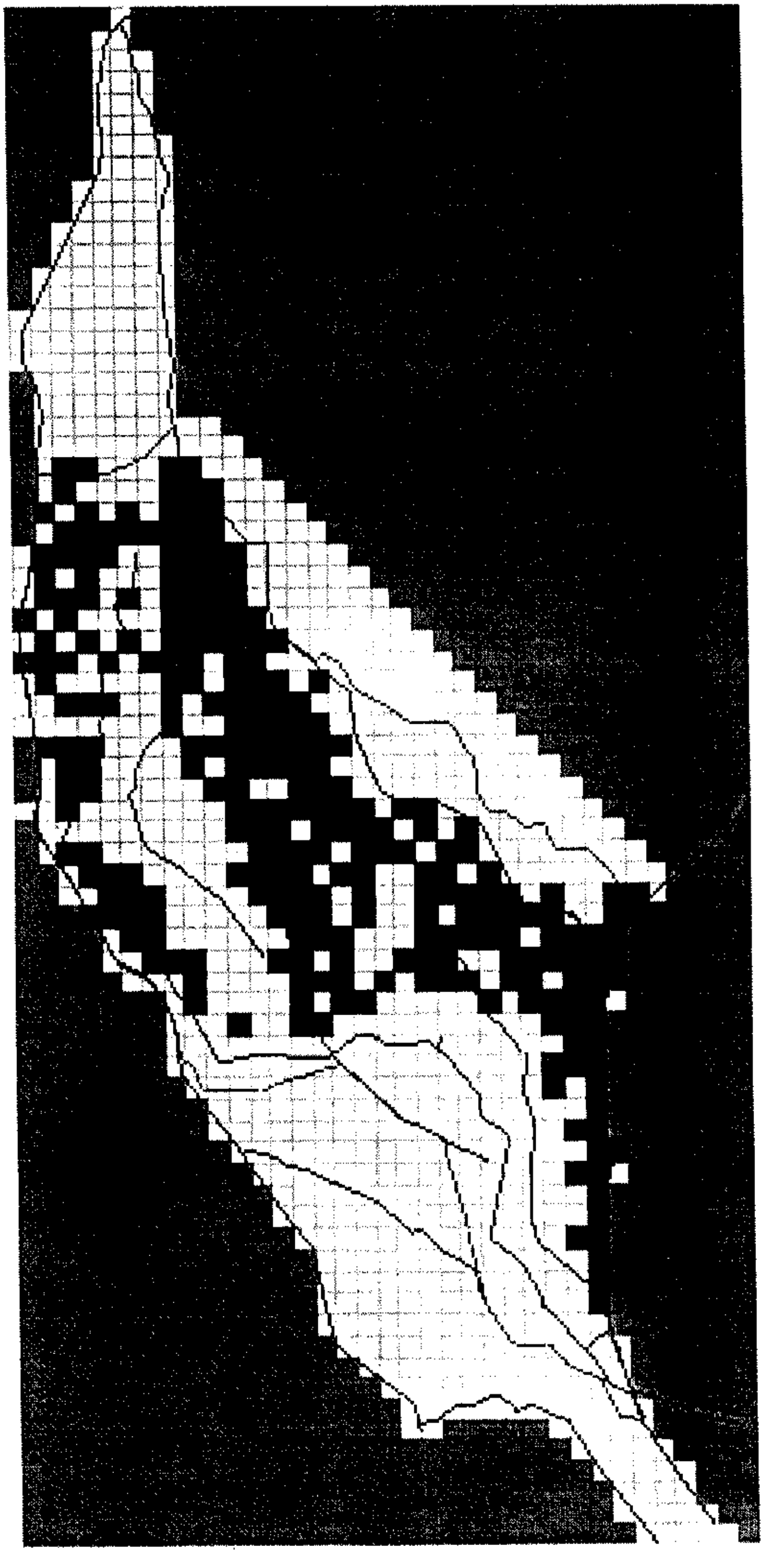


Figure 5. Locations of Pumping Cells in the LBOD-Nawabshah study area.

4 MODFLOW considers the uniform rate of operation of the tubewell during a stress period. Therefore, numbers of working hours in a stress period for every tubewell are deteremined from the OMD monthly operational status of the LBOD-Nawabshah tubewells, along with actual discharge rates.

5 The volume of groundwater extracted during the stress period is obtained by multiplying the rate of pumping with the duration of pumping calculated.

6 The uniform rate of operation of a tubewell during a stress period is then estimated by dividing the volume by the number of days in the stress period.

7 Rates of operation of two or more tubewells, located in the same pumping cell, are simply summed up arithmetically.

▸ River Package

The LBOD-Nawabshah Component Project is located between the Rohri Main Canal and the Jamrao Canal, and has perennial irrigation supplies. The modeled area is bounded and commanded by the Rohri Main Canal (100 km to 246 km~RD 328 to 807, 1RD = 1000 ft.) on the western boundary, while the Jamrao Canal (15 km to 81 km~RD 49 to 266) constitutes the eastern boundary. Both canals have been modeled as rivers in the mathematical model to estimate the leakage to groundwater.

The Nasrat Branch Canal system, with a discharge of more than 55 cumecs (2,000 cusecs), is the largest branch outlet on the Rohri Main Canal. This system supplies water to majority of the modeled area to fulfill the irrigation needs. The head reach of the Nasrat Branch also constitutes the boundary of the modeled area to the north. The system, composed of Nasrat (96 km~316 RD), Amurji (25 km~81 RD), and Gajrah (28 km~91 RD) Branches, is modeled as river. The Channa Distributary (18 km~58 RD) that follow the Nasrat Branch and the Shahpur Distributary (17 km~55 RD) following the Channa Distributary are included in the river package representing as Nasrat Branch subsystem. Similarly, James (15 km~51 RD) and Nawabshah (13 km~43 RD) Distributaries, the Amurji subsystem and Chan Babu Distributary (25 km~82 RD) of the Gajrah Branch subsystem are included in the river package.

Also included in the river package are the Ali Bahar Branch Canal (6 km~21 RD) system and the Jam Branch canal (22 km~70 RD) system of-taking from the Rohri Main Canal to the study area. Lundo Distributary (22 km~71 RD) and Berani Distributary (13 km~41 RD) are included in the river package as pact of the Ali Bahar and Jam Branch Canal systems, respectively. The Jam Branch system also constitutes the southern boundary of the modeled area.

Implementation of the River Package involved the following:

1 Alignments for main and branch canal systems are digitized using satellite imagery (Figure 6). The model grid is placed over the digitized map to ease identification and river-reach length measurements in a grid cell.

2 The measured lengths of canals are compared with the as-built lengths of canals, and correction factors applied as needed. In each grid cell containing a canal, the RD point where the canal discharges out of the cell is calculated.

3 Profile data of hydraulic structures (cross regulator, fall structure regulator, bridge, etc.) providing RD, bed level (BL), bed width (B), and full supply level (FSL) for each modeled canal is obtained from the Sindh Irrigation and Power Department.

4 For a particular RD, these profile values are calculated using linear interpolation.

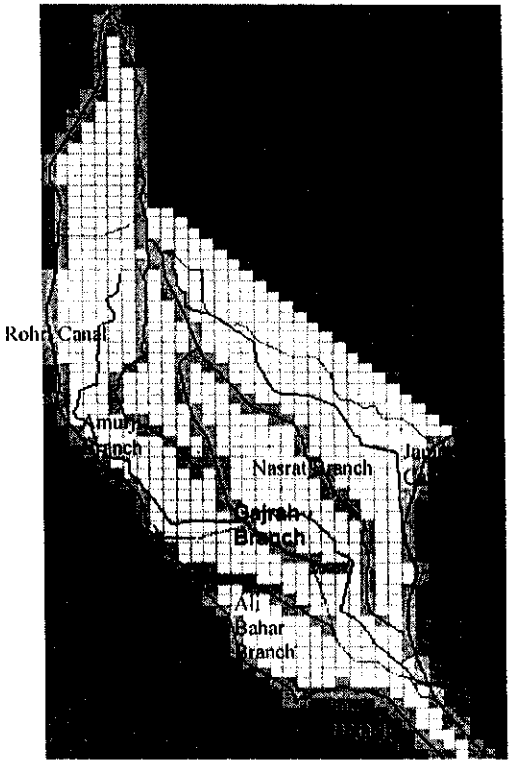


Figure 6. The Main and Branch Canal Systems in the Study Area Modeled as Rivers.

5. For a modeled grid cell containing the canal, the average values across the two RDs' (entry and exit points in a grid cell) are taken.
6. The seepage analyses on various canals/streams in the model area have been reported by the International Irrigation Management Institute (Lashari et al.,1997) and Siddique and Ali (1997). An average seepage rate of 1.524×10^{-6} m/s (equivalent to 5 cusec/million square feet of wetted area) is adopted as the vertical hydraulic conductivity (K) of the bed material of the canal.
7. The river cell conductance is used in MODFLOW to calculate the groundwater flow to and from the river, depending on the groundwater head and stage in the river cell. The conductance (m^2/d) is estimated using the relationship:

$$\text{Conductance} = \frac{KWL}{M}$$

Where, K is the vertical hydraulic conductivity of the river bed material (m/d), W is the wetted perimeter of the river (m), L is the length of the river reach in a cell (m), and M is the thickness of the bed material (m). Half value of the respective conductance for the Rohri Main Canal, Jamrao Canal, head reach of the Nasrat Branch, and the Jam Branch system has been used, as the model area is on one side of these canals. During the Rabi season/stress period, the conductance values are reduced to 80 percent according to operating conditions of canals.

The details of each river system for the model are given in Annexure-I, Table B.

Recharge Package

The conveyance losses from distributaries, minors, watercourses and field application losses on the farm are the major sources of uniform areal recharge to a grid cell in the model area. A list of distributaries and minors, along with salient features in the model area, is shown in Annexure-I, Table C.

The other sources of recharge are rainfall and seepage losses from open drains. The seasonal records of rainfall data for the Nawabshah and Padidan weather stations are shown in Table 2.

Table 2. Seasonal Rainfall Recorded in the Nawabshah and Padidan Weather Stations.

Season	Rainfall (mm)	
	Nawabshah	Padidan
Kharif 1988	22.0	56.9
Rabi 1988-89	6.1	7.6
Kharif 1989	59.1	52.4
Rabi 1989-90	5.1	20.1
Kharif 1990	174.6	68.5
Rabi 1990-91	7.4	14.3
Kharif 1991	0.0	42.8
Rabi 1991-92	23.5	67.1
Kharif 1992	362.7	480.8
Rabi 1992-93	31.0	27.3
Kharif 1993	18.6	76.3
Rabi 1993-94	3.2	10.1
Kharif 1994	544.2	233.9
Rabi 1994-95	45.0	43.2
Kharif 1995	200.3	175.1
Rabi 1995-96	4.2	12.1
Kharif 1996	1.0	51.2

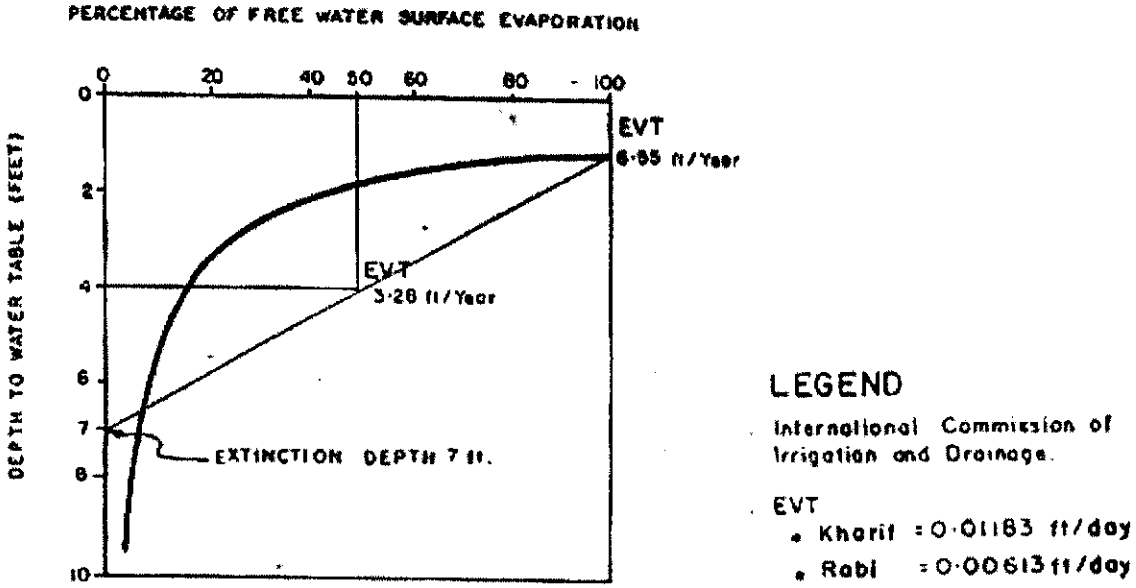
(Source: SMO (South), WAPDA, 1997)

Also, a number of private shallow open wells and tubewells are distributed in the modeled area for augmentation of relatively usable saline groundwater. The locations and operational status of these wells are not known, nor maintained. In this model study, the areally uniform net recharge term is utilized for each grid cell which takes into account the lumped effect of different uniformly distributed recharge and discharge mechanisms. The net recharge is adjusted during the calibration process.

Evapotranspiration Package

The loss of water directly from the unconfined aquifer occurs when the water table is at, or close to, the natural surface. This loss of water decreases as the depth to water table increases and ceases at some depth known as the extinction depth. The process is a capillary upflow phenomenon and accounts for a considerable amount of water outflow in the groundwater volume balance. This is clearly of major importance in the Lower Indus Basin under the present conditions, especially in the model area.

The LIP study (1965) developed and compared a curve representing the capillary upflow phenomenon in the region at various water table depths as the percentage evaporation from the free water surface. The SSTNRPP groundwater model (1997) utilized the linear approximation of the curve (Figure 7) to be represented in the evapotranspiration package of MODFLOW. Different maximum evaporation rates for stress periods (0.0036 $m^3/m^2/d$ for the Kharif season and 0.0019 $m^3/m^2/d$ for the Rabi season), with the natural surface as the maximum evaporation surface and extinction depth of about 2 m, are utilized for modeling purposes. As the study area is adjacent to the SSTNRPP groundwater model area, the same parameters are used in the evapotranspiration package of the LBOD-Nawabshah groundwater model to represent the capillary upflow phenomenon.



Source: Annexure III, Hydrogeological and Groundwater Mathematical Studies, Completion Report, SSTNRPP (ACE et al., 1997).

Figure 7. A Linear Approximation of Evaporation from the Water Table at Different Depths.

IV. MODEL CALIBRATION

A calibrated groundwater model demonstrates the model's ability to reproduce the hydrologic conditions of the natural system in terms of field-measured heads and/or flows. The limitation of field data introduces uncertainties in specifying aquifer and model parameters to every grid cell. As a result, the initial model execution seldom reproduces the natural hydrologic conditions. The calibration process involves trial-and-error adjustments of aquifer parameters, boundary conditions, and stresses in successive model runs to obtain an acceptable match between the simulated and measured field values (Anderson and Woessner, 1992). Because of the ease and accuracy in the measurement, groundwater heads or seasonal water level trends are matched in a transient model. Field-measured values of heads are called calibration values and are associated with error or calibration criterion to establish the calibration target.

SCARPs Monitoring Organization (SMO), WAPDA (South), has a mandate to measure and report water table fluctuations in the LBOD Stage-I Project (and other areas of the Sindh province) due to tubewell drainage developments. In the LBOD-Nawabshah groundwater model area, there are more than 300 such locations where biannual measurements of depth to water table (April-beginning of the Kharif season and October-beginning of the Rabi season) are recorded and reported. The depth to water table data is collected from piezometers, open wells, tubewell bore holes and three automatic stage recorders (complete data available for the last few years only due to the maintenance problem) installed in the LBOD-Nawabshah Component Project area at Bandhi, Sathmile and Shahpur Chakar. The locations of most of the observation points in terms of Northing and Easting are also reported by the SMO (1997) while remainders are digitized. The available depth to water table data for each season/stress period and period of calibration (1988 to 1998) are processed and gridded using the Field Interpolator capability of PMWIN on the model domain. The generated gridded values are subtracted from the digital elevation model of the area in order to obtain gridded water level readings.

The calibration of the LBOD-Nawabshah groundwater model consists of dividing the model area into zones, selecting key observation locations, establishing calibration values, criteria and targets, and preparing the water balance for the model area. The aquifer parameters and stress packages are adjusted in the calibration process to match the gridded field-measured water levels and flows with the simulated ones. The methodology adopted a series of model runs to check the sensitivity over a range of these parameters.

A. ZONES

The model domain is divided into twenty zones. A zone is a group of grid cells with similar net recharge characteristics, selected on the basis of the area between the irrigation branch/canal (Figure 8). The salient features of each zone are given in Table 3.

B. KEY OBSERVATION LOCATION

The model is calibrated against hydrographs of the selected water table observation locations and termed as key observation locations. The selection of these locations is made on the basis that the points are well scattered over the entire model area, data are available for maximum periods, and data show some trends for different stress periods. Thirty locations (identified as 1 through 30, Figure 9) have been selected, comprising a minimum of one observation location in each zone (except the desert zone, which is not calibrated).

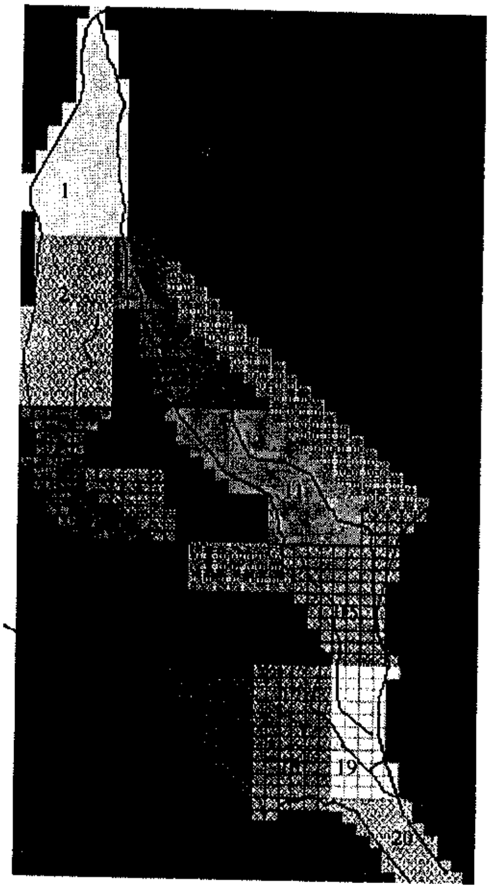


Figure 8. Selected Zones in the LBOD-Nawabshah GWM Domain.

Table 3. Salient Features of Zones used in the LBOD-Nawabshah GWM Domain.

Zone	Location	Cells (#)	Channels (#)	DTW (#)	STW (#)	TW (#)	OBL (#)	Key OBL (ID)
1	Rohri-Nasrat	97	9				31	29, 30
2	Rohri-Amurji	92	6	41		41	29	1, 2
3	Nasrat-Bound	24	1	12	22	34	6	5
4	Amurji-Nasrat	21	2	32	12	44	13	3, 4
5	Nasrat-Desert	47	3	13	24	37	12	6
6	Desert	81	-				9	
7	Rohri-Amurji	55	8	23		23	14	7, 8
8	Amurji-Gajrah	22	2	5		5	8	9
9	Amurji-Gajrah	26	1	4		4	8	10
10	Gajrah-Nasrat	50	8	43	10	53	14	11, 12
11	Nasrat-Desert	89	5	43	38	81	27	13, 14
12	Rohri-Gajrah	72	5	4	3	7	19	15, 16
13	Gajrah-Nasrat	28	3	15		15	10	17
14	Gajrah-Nasrat	42	4				14	18
15	Nasrat-Jamrao	81	5	34	56	90	25	19, 20
16	Rohri-Ali Bahar	46	5				14	25, 26
17	Ali Bahar-WNMD	36					11	21
18	Rohri-Jam	38	1				12	22
19	WNMD-Jamrao	48	2	7	24	31	16	23, 24
20	Jam-Jamrao	35	1				18	27, 28
	Total	1030	71	276	189	465	310	

(where; channels-distributaries and minors, DTW-drainage tubewells, STW-Scavenger tubewells, TW=DTW+STW-Tubewells, and OBL-water table observation locations)

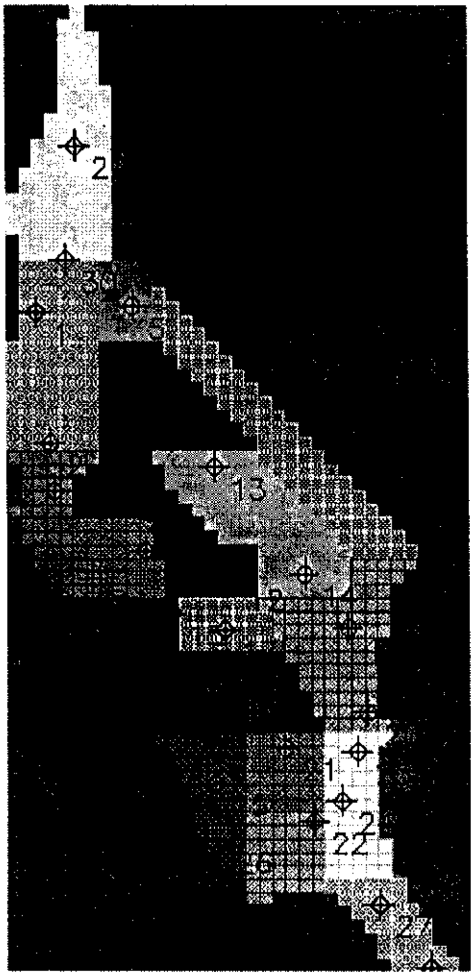


Figure 9. Key Observation Locations in the LBOD-Nawabshah GWM Domain.

C. CALIBRATION CRITERIA AND TARGET

The hydraulic conductivity, specific yield and stress packages are adjusted one by one in the calibration process. The resulting heads are compared with the gridded head values of the key observation locations. The adjustments in the parameter values are made on the zonal basis, until the trend of the simulated and gridded water levels matched and the difference remained within a minimal range. Net recharge values principally dominated the calibration process of the model, while other parameters and stress packages showed less sensitivity to change in heads. The contour maps of measured and simulated groundwater levels (Annexure II, Figure II.1 to II.20) matched closely and showed similar groundwater flow trends in the model domain. The root mean squared error (RMSE) for each key observation location is computed to evaluate the calibration process quantitatively. The compared hydrographs at the key observation locations, along with RMSE values, are shown in Figures 10 to 17.

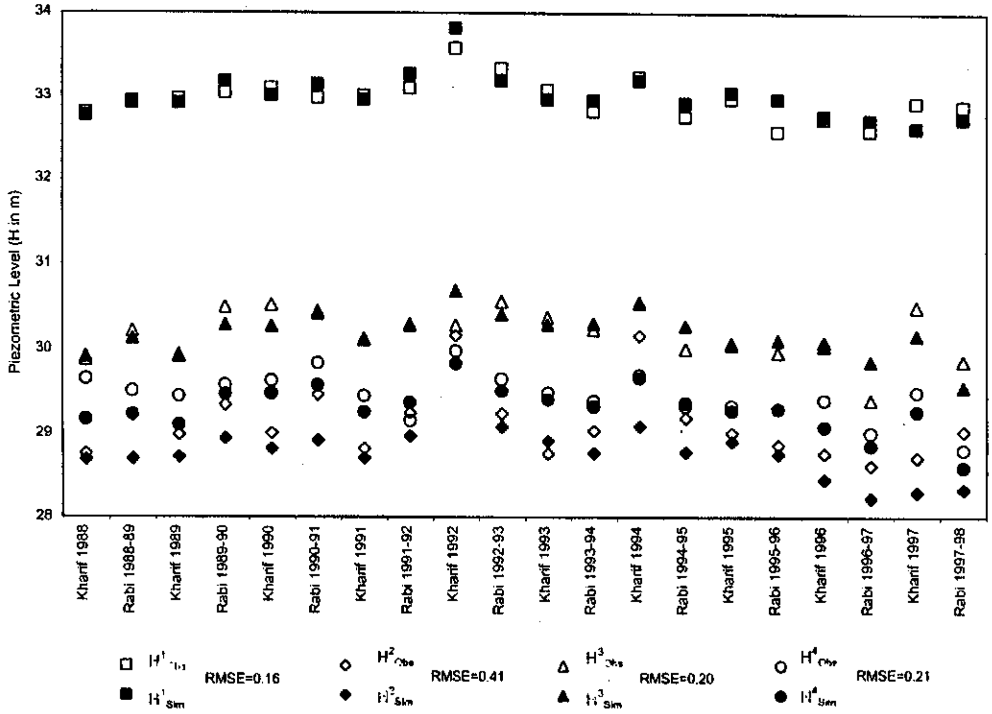


Figure 10. Observed and Simulated Piezometric Levels for Key Observation Locations 1 to 4.

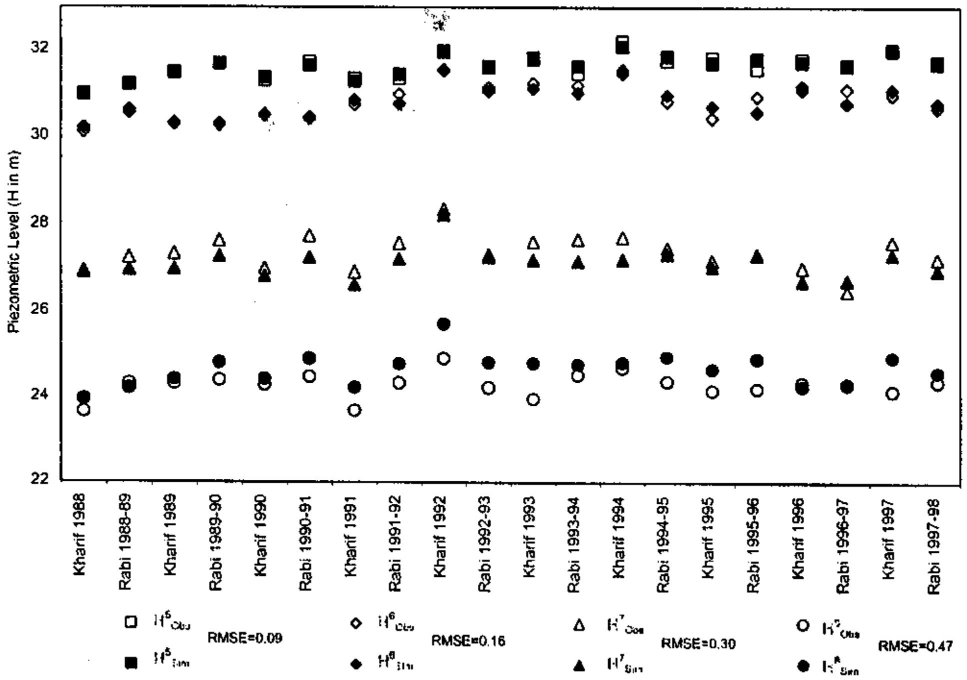


Figure 11. Observed and Simulated Piezometric Levels for Key Observation Locations 5 to 8.

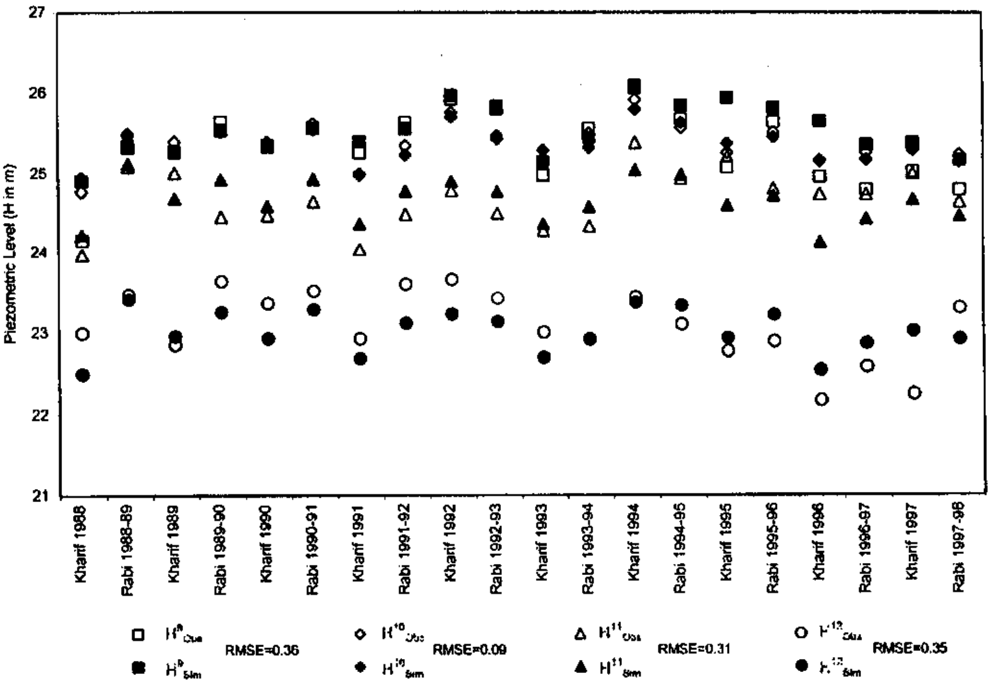


Figure 12. Observed and Simulated Piezometric Levels for Key Observation Locations 9 to 12.

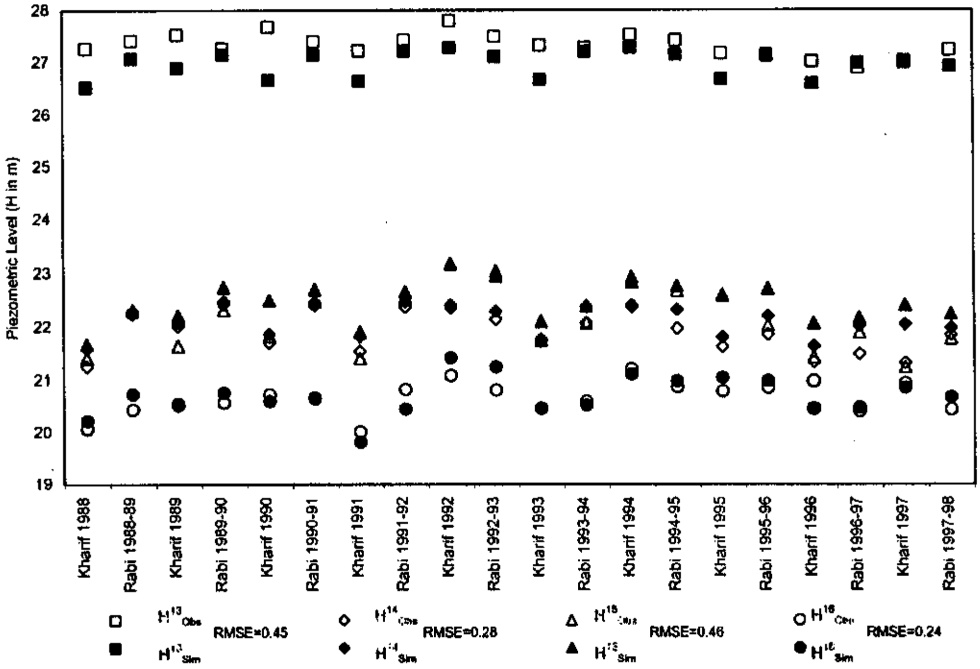


Figure 13. Observed and Simulated Piezometric Levels for Key Observation Locations 13 to 16.

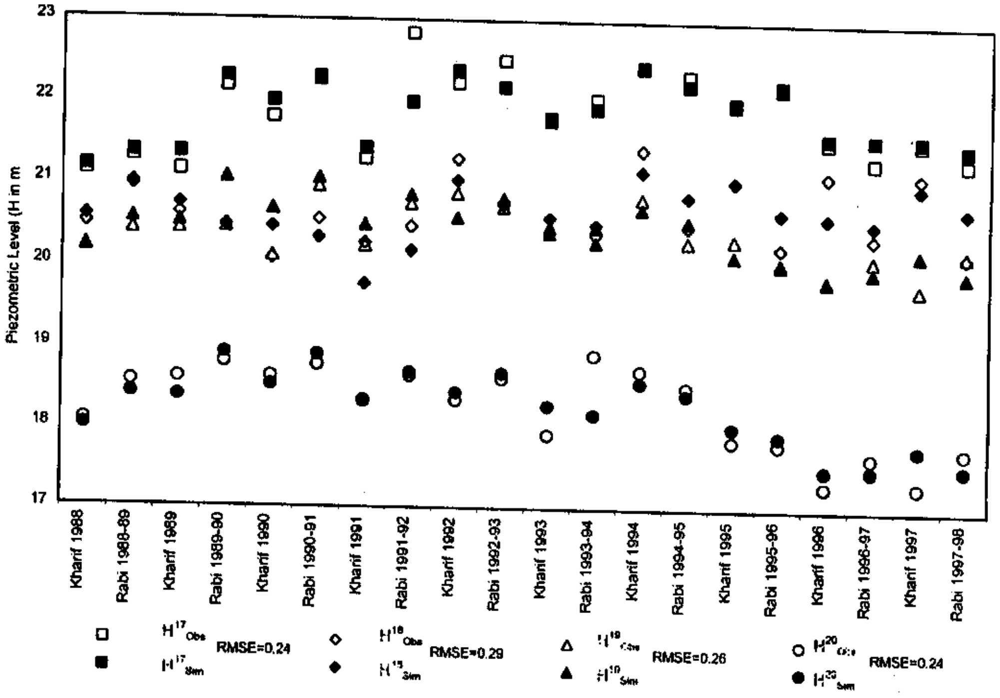


Figure 14. Observed and Simulated Piezometric Levels for Key Observation Locations 17 to 20.

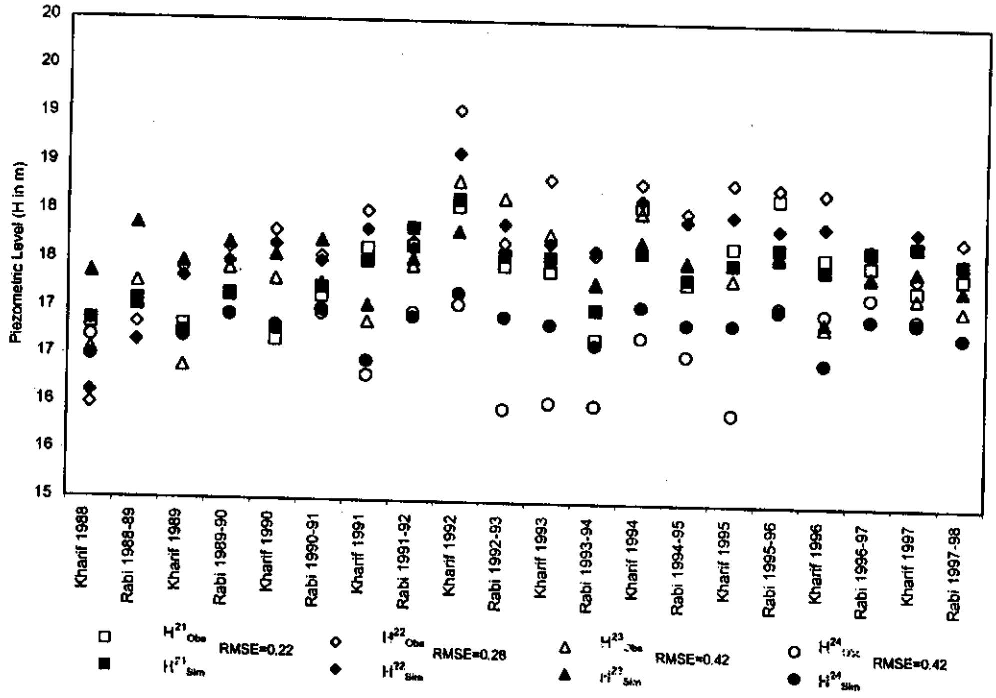


Figure 15. Observed and Simulated Piezometric Levels for Key Observation Locations 21 to 24.

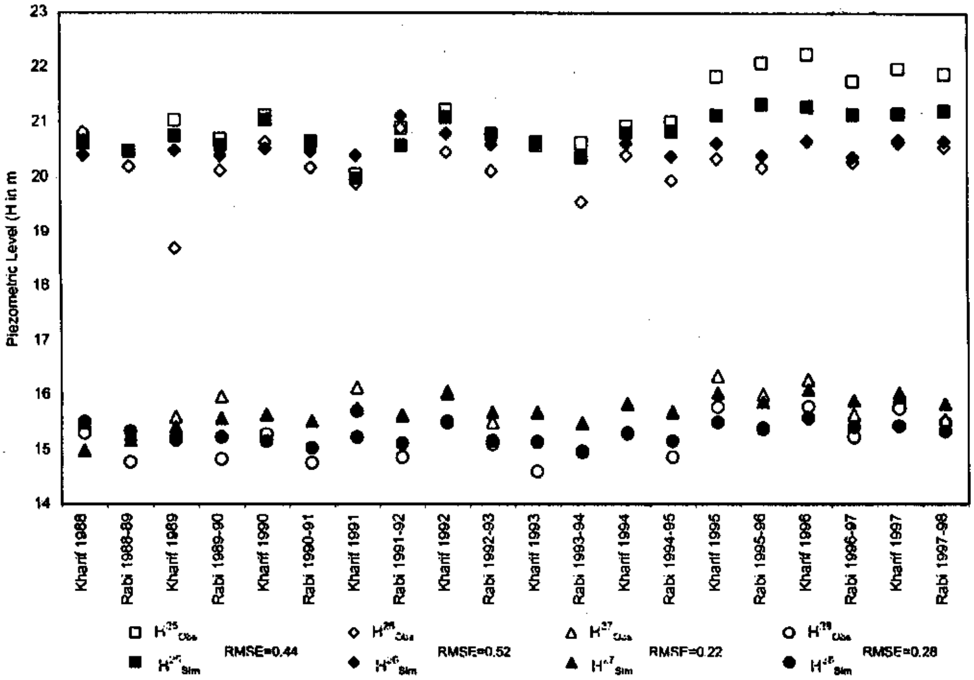


Figure 16. Observed and Simulated Piezometric Levels for Key Observation Locations 25 to 28.

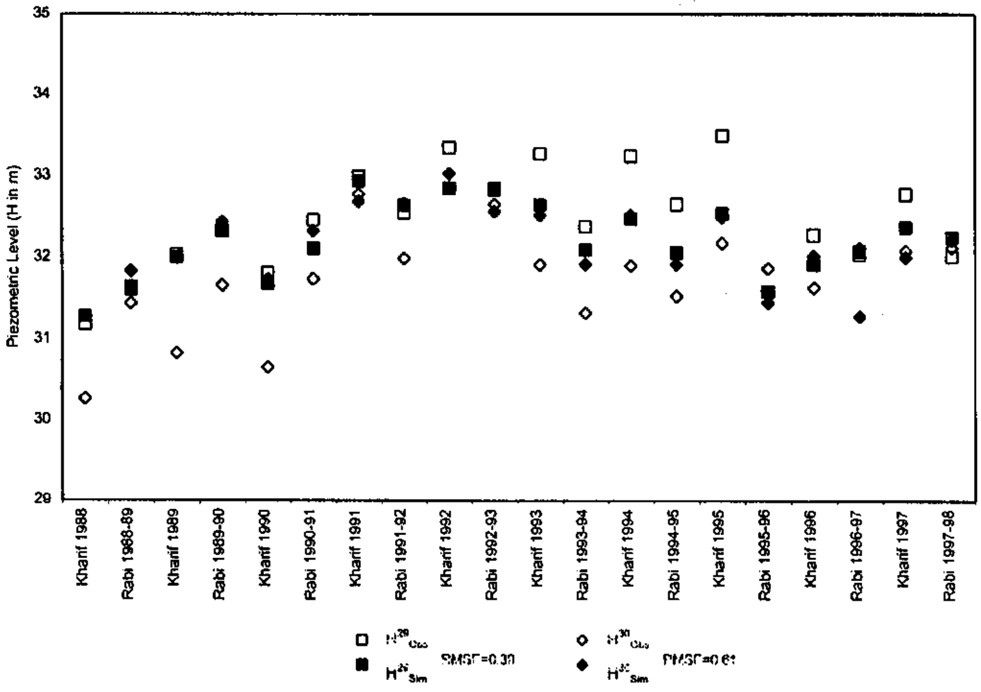


Figure 17. Observed and Simulated Piezometric Levels for Key Observation Locations 29 and 30.

D. WATER BALANCE

The water balance for the groundwater sub-system and the overall water balance for the model area are calculated for every season using simulated results (Table 4). The inflows to the groundwater sub-system consist of net recharge and seepage from the canals/branch systems, while capillary upflow and pumping are the outflows. The overall system inflows are expressed in terms of canal water supplies and rainfall, while outflows are pumping and evpotranspiration, along with the change in soil moisture storage.

Table 4. The Overall System and Groundwater Sub-system Water Balances for the LBOD-Nawabshah GWM Area.

Groundwater Sub-system (mm/d)						Overall System (mm/d)				
StressPeriod	GW Net Recharge (A)	Main and Branch Canal Leakage to GW (B)	GW Storage Change (C=A+B-D-E)	Capillary Upflow (D)	Pumping (E)	Canal Water Supply (F)	Rainfall (G)	GW Storage Change (H)	Evapotranspiration and Soil Moisture Change I=F+G-H-J)	Pumping (J)
Kharif 1988	0.005	0.19	-0.09	0.28		1.73	0.21	-0.09	2.03	
Rabi 1988-89	0.55	0.14	0.36	0.33		1.38	0.04	0.36	1.06	
Kharif 1989	0.37	0.19	0.02	0.53		1.73	0.30	0.02	2.01	
Rabi 1989-90	0.58	0.14	0.27	0.44		1.38	0.07	0.27	1.18	
Kharif 1990	0.22	0.19	-0.16	0.57		1.73	0.66	-0.16	2.55	
Rabi 1990-91	0.49	0.14	0.19	0.43		1.38	0.06	0.19	1.25	
Kharif 1991	0.11	0.19	-0.27	0.57		1.73	0.12	-0.27	2.12	
Rabi 1991-92	0.64	0.14	0.33	0.44		1.38	0.25	0.33	1.30	
Kharif 1992	1.42	0.19	0.35	1.26		1.73	2.29	0.35	3.68	
Rabi 1992-93	0.08	0.14	-0.27	0.49		1.38	0.16	-0.27	1.82	
Kharif 1993	0.15	0.19	-0.24	0.58		1.73	0.26	-0.24	2.23	
Rabi 1993-94	0.13	0.14	-0.05	0.32		1.38	0.04	-0.05	1.47	
Kharif 1994	1.09	0.19	0.32	0.96		1.73	2.11	0.32	3.53	
Rabi 1994-95	0.09	0.14	-0.18	0.40		1.38	0.24	-0.18	1.80	
Kharif 1995	0.40	0.19	-0.04	0.63		1.73	1.02	-0.04	2.79	
Rabi 1995-96	0.25	0.14	-0.05	0.35	0.09	1.38	0.05	-0.05	1.39	0.09
Kharif 1996	0.16	0.19	-0.18	0.40	0.12	1.73	0.79	-0.18	2.58	0.12
Rabi 1996-97	0.25	0.14	0.02	0.26	0.11	1.38	0.10	0.02	1.35	0.11
Kharif 1997	0.69	0.19	0.16	0.61	0.12	1.73	0.79	0.16	2.24	0.12
Rabi 1997-98	0.08	0.14	-0.17	0.25	0.13	1.38	0.10	-0.17	1.53	0.13

V. SIMULATIONS, RESULTS AND DISCUSSIONS

The purpose of this study is to develop and compare different operational strategies for tubewells installed under LBOD-Nawabshah Component Project using the calibrated groundwater model of the area. The comparison is made in terms of the extent of area under the influence of waterlogging resulting from the implementation of a strategy. The area is considered waterlogged if the depth to water table is within 1.5 m, and termed as a critical area. The critical areas are identified by simulating the behavior of the groundwater using developed model and subtracting the computed groundwater head distribution from the natural surface levels. The depth to water table distribution is plotted to identify grid cells located in the critical area. Herein, the strategy that reduces the drainable surplus with a reasonable control of critical areas would be selected.

The calibrated LBOD-Nawabshah groundwater model is used to simulate the aquifer response up to the year 2010. The model simulates from April 1988 to April 2010 for 44 stress periods. The application of the developed model is limited to the appraisal of pre- and post-LBOD Stage-I Project developments in the study area, and the evaluation of predictions based on the continuation of the existing practices and implementation of proposed practices. The following scenarios are compared:

- April 1993-Before Functional Tubewells
- April 1998-Current Management Practices
- April 2010-Continuation of Existing Practices
- April 2010-Tubewells Operation at Installed Capacity
- April 2010-Tubewell Operation at Installed Capacity in Critical Areas only

A. SCENARIO 1, APRIL 1993 — BEFORE FUNCTIONAL TUBEWELLS

The extent of waterlogging in the component project area prior to the drainage tubewells operation is observed in this scenario. This consists of the conversion of simulated water levels to the depths to water table and identification of areas where the water table is within 1.5 m depth. These areas are termed as critical areas and are in need of subsurface drainage for an adequate root zone environment. A contour map of the depth to water table, showing the extent of critical areas, is depicted in Figure 18. A large area under the influence of waterlogging can be observed. An analysis over the grid area shows that 527 cells (51 percent of the study area) are affected with high water table and are in need of subsurface drainage.

B. SCENARIO 2, APRIL 1998 — CURRENT MANAGEMENT PRACTICES

This scenario compares the extents of critical areas as a result of the operation of the LBOD-Nawabshah drainage tubewells under the current management, which comprise extraction of saline drainable surplus at the rate of 526,958 m^3/d. The depth to water table contour map, showing the extent of critical area, is depicted in Figure 18. The operation of drainage tubewells has shown a reduction in the extent of critical areas; still, a significant area is waterlogged. The critical area is now limited to 257 grid cells (25%) of the study area, while tubewells are running at 41 percent of the installed capacity.

This scenario can be considered as the base line from the management point of view, as the tubewells are operated randomly depending upon the operating conditions. A large portion of the study area on the northeastern side is under the influence of waterlogging.

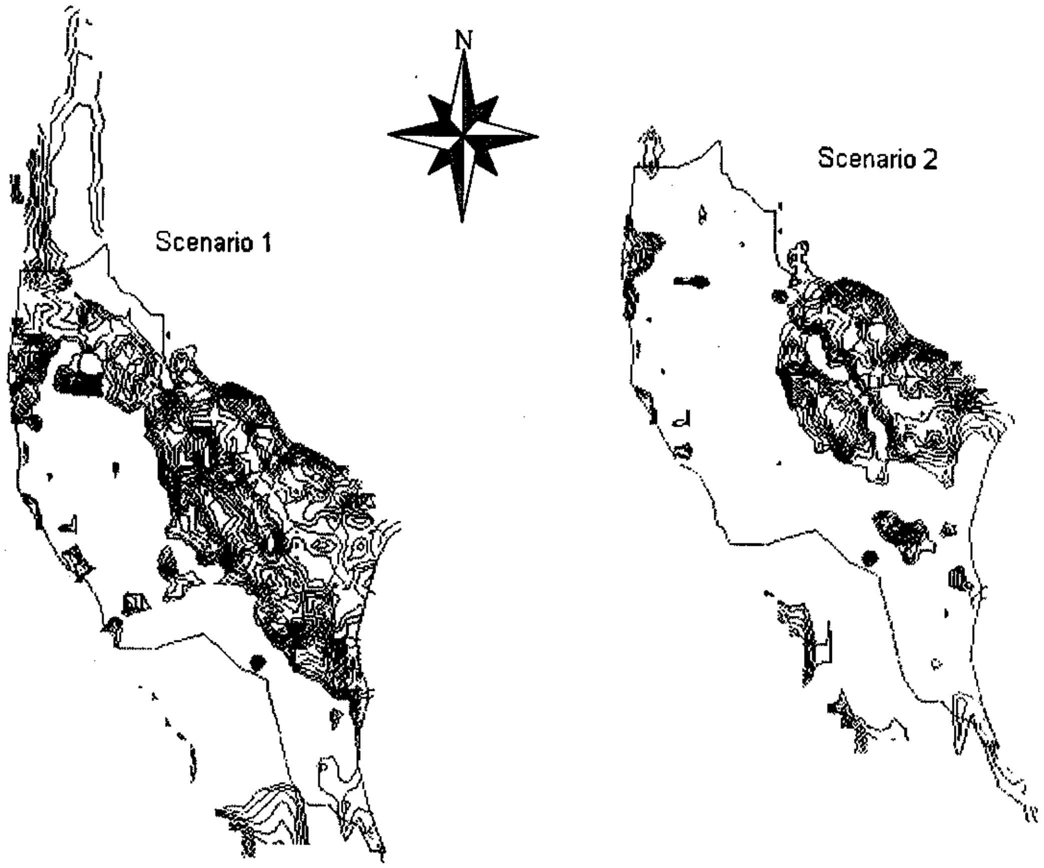


Figure 18. Scenario 1 and 2 — Extent of Areas with Water Table within 1.5 m of the Ground Surface.

C. SCENARIO 3, APRIL 2010 — CONTINUATION OF EXISTING PRACTICES

The prediction of the resulting water level due to the continuation of the existent management of drainage tubewells (526,958 m^3/d) up to the year 2010 is simulated. The depth to water table is drawn in the shape of a contour map (Figure 19) which shows a reduction in the extent of critical areas.

This scenario is about maintaining the operation of tubewells at the current rate up to the year 2010 and predicting the response of the water table. The extent of critical area is limited to 245 grid cells when compared to 257 cells in the previous scenario. Hence, *the continuation of existing operational strategy would not make an appreciable difference in the reduction of critical areas in the long run.*

Figure 19. Scenario 3 — Extent of Areas with Water Table within 1.5 m.

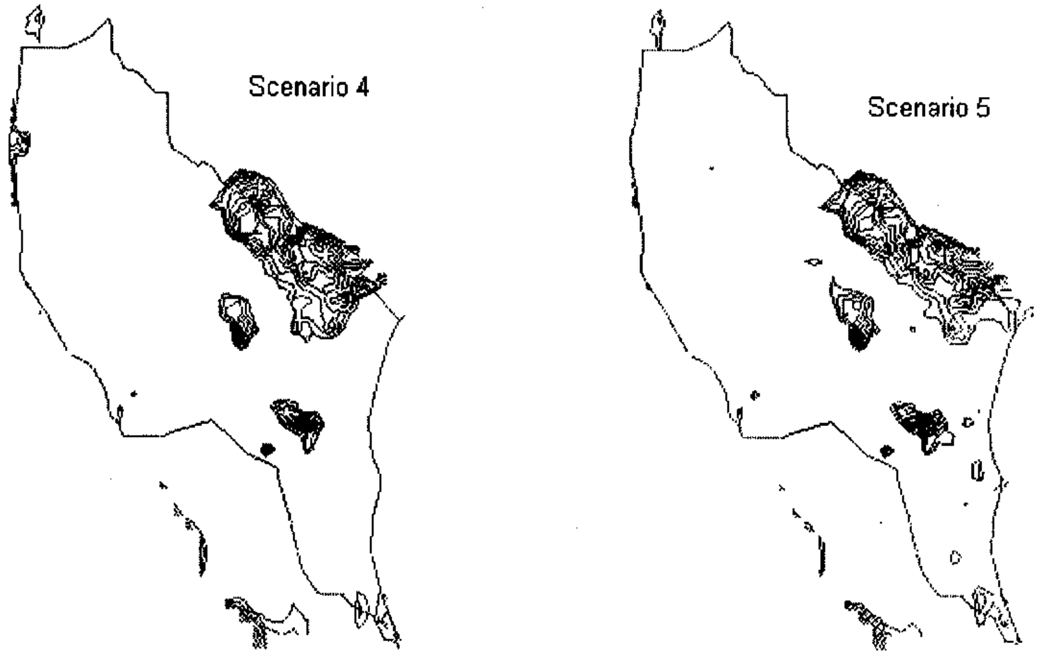
D. SCENARIO 4, APRIL 2010 — TUBEWELLS OPERATION AT INSTALLED CAPACITY

The design of the subsurface drainage system for the LBOD-Nawabshah Component project identified the areas of high water table and distributed tubewells mainly on the northeastern and western sides of the study area. The operational design consisted of tubewells operating 14-hours-a-day in these areas to maintain the water table at 1.5 to 2 meter depth. This scenario is run to check the effects of operating all the component project tubewells at the installed capacity irrespective of critical areas. *Under this scenario, the drainable surplus amounts to an extraction of 1,290,217 m^3/d of saline groundwater.* The resulting distribution of groundwater heads is simulated up to the year 2010. The depth to water table contour map (Figure 20) shows a remarkable reduction in critical areas and limits waterlogging to only 123 grid cells (12%) of the study area, mostly located in the northeast. This scenario may also be considered as the most expensive operating strategy, as all tubewells will be operating at full installed capacity.

E. SCENARIO 5, APRIL 2010 — TUBEWELLS OPERATION AT INSTALLED CAPACITY IN CRITICAL AREAS ONLY

This is the proposed management scenario where tubewells in the critical areas are set to operate at the installed capacity, while tubewells in other areas are operated at existent rates. This scenario consists of identifying tubewells located in, and near to, the critical areas. The operating rates of such tubewells are changed to the maximum rates and simulating the effects by running the model. *This scenario has also shown a remarkable reduction in critical areas (Figure 20), while saline drainable surplus is 912,337 m^3/d.* There are 163 grid cells (16% of the study area) that would remain waterlogged under this scenario.

This scenario shows promise over others in terms of limiting the waterlogged areas, as tubewells save up to 30 percent in terms of drainage effluent, operational time and energy.



Scenario 4

Scenario 5

Figure 20. Scenario 4 and 5 — Extent of Areas with Water Table within 1.5 m.

It can be noticed from the results of above simulations that the northeastern portion of the component project area is consistently waterlogged. The LBOD-Nawabshah GWM in this portion of component project area may be interpreted with caution as the portion constitutes the boundary of irrigated area and contains sand dunes/fringes of desert along with open water bodies/marshes. The extrapolated natural surface level values for this portion of the component project might not be representative for the calculation of depths to water table.

VI. CONCLUSIONS AND RECOMMENDATIONS

The groundwater model is an efficient and useful tool to simulate the behavior of the aquifer under different pumping rates and patterns. The LBOD-Nawabshah groundwater model is successfully developed, calibrated and applied to simulate aquifer response up to the year 2010. The current and future management strategies for the operation of drainage tubewells are compared in terms of the extent of areas with depth to water table within 1.5 m, termed as critical areas. The depth to water table contour maps for different strategies identified the critical areas on the model domain and showed the extent of these areas. The proposed strategy of operating tubewells in critical areas at the installed capacity and remaining at the prevailing rates of extraction showed a significant reduction in critical areas and a saving in operating time and drainable surplus. The proposed strategy showed promise over the current management strategy and strategy of operating tubewells at designed/installed capacity in the component project area, in terms of both reducing the extent of critical areas and amount of highly saline drainable surplus. The following general conclusions can be made based on the LBOD-Nawabshah groundwater modeling study:

- The aquifer underlying LBOD-Nawabshah GWM study area is highly saline, transmissive, and unconfined with pockets of fresh water lenses along the main and branch canals;
- The direction of groundwater flow is towards the southeast and away from the Rohri Main Canal;
- The elevated main and branch canal systems are acting as the recharge source for groundwater system;
- A comparison with the Second SCARP Transition North Rohri Pilot Project's (SSTNRPP) hydrogeological and groundwater mathematical model studies suggests that the Rohri Main Canal is acting as a hydrologic divide between the SSTNRPP and LBOD-Nawabshah study areas. This also supports the selection of river cells as recharging boundary of the study area;
- The model is successfully calibrated against selected key observation locations with root mean square errors (RMSE) of observed and simulated piezometric levels within 0.50 m;
- The net recharge considered in the study is areal flux to groundwater consisting of distributaries, minors, watercourses and field applications losses, rainfall contribution, unaccounted groundwater extraction and return flow from pumped water. *The LBOD-Nawabshah GWM has shown high sensitivity to the net recharge in this flat terrain basin*;
- The current operation practice (April 1998) of tubewells (526,958 m^3/d—41 percent of the installed capacity) in the LBOD-Nawabshah component project area has shown reduction in the extent of waterlogged areas. This area is now 25 percent of the study area as compared to 51 percent in April 1993 without tubewell operation. The continuation of the same practice in future will not reduce the waterlogged area significantly. *The LBOD-Nawabshah GWM predicts that 24 percent of the area will remain waterlogged*;
- The management of operating all tubewells at installed capacity requires extraction of 1,290,217 m^3/d saline groundwater with reduction of waterlogged area to mere 12 percent; and
- The proposed strategy of operating tubewells in waterlogged area only at installed capacity and remaining at the current rate, shows 30 percent saving in saline

drainable surplus as well as adequately limiting the waterlogged area to 16 percent.

Testing of various management interventions is made possible through the development of the LBOD-Nawabshah groundwater model. The validity of predictions is always questioned in groundwater development exercises. Therefore, it is recommended that the groundwater monitoring and changes in hydrological conditions (in comparison to those used for calibration) should be carefully incorporated in the model to predict impacts on hydrodynamics of the aquifer.

An optimization of the groundwater system can provide further refinement to management strategies. This involves incorporation of various limitations and constraints of the hydrogeologic system and operation of tubewells while selecting the best management strategy for improved subsurface drainage. The methodology computes the pumping strategy that satisfies the goals in an optimal manner with the inclusion of both simulation equations and an operation research optimization algorithm. The simulation equations permit representation of aquifer response to hydraulic stimuli and boundary conditions while the optimization algorithm allows the specified management objective to search as the function driving the search for an optimal strategy. Hence, in comparison to a simulated pumping strategy the optimization approach computes the pumping strategy. Therefore, it is recommended that further research may be carried out to develop optimal strategies for drainage tubewell operations in the LBOD-Nawabshah component project area using the developed groundwater model.

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ANNEXURE I
TABLES

Table A. East Nawabshah, West Nawabshah and Nawabshah Scavenger Tubewells.

S. No.	East Nawabshah Tubewells				West Nawabshah Tubewells				Nawabshah Scavenger Tubewells				
	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	QFresh (lps)	QSaline (lps)
1	EN-2	2178167	999918	57	AM-09	2174778	987282	46	AM-01	2175062	1000164	32	14
2	EN-5	2178972	997954	59	AM-10	2174746	985410	44	AM-02	2175844	997743	30	14
3	EN-9	2179971	996175	59	AM-11	2174469	983634	47	AM-03	2175736	996354	32	19
4	EN-13	2181082	993552	58	AM-12	2174355	981520	53	AM-04	2175442	994551	16	29
5	EN-16	2180147	991965	59	AM-13	2174331	978447	48	AM-05	2175158	993684	18	31
6	EN-20	2181019	989860	60	AM-14	2175838	976947	51	AM-06	2175220	991872	17	29
7	EN-27	2183585	986100	57	AM-15	2175433	979011	54	AM-07	2175326	990581	23	20
8	EN-32	2184744	984743	58	AM-16	2175594	981130	54	AM-08	2175213	988998	23	20
9	EN-38	2185405	981702	58	AM-17	2176076	982961	44	AM-20	2175937	988031	17	30
10	EN-44	2186346	979693	61	AM-18	2176127	984700	43	AM-21	2175916	989882	27	23
11	EN-45	2188611	980679	60	AM-19	2176274	986811	47	AM-22	2176584	991065	27	42
12	EN-50	2185243	977470	60	AM-25	2176513	995024	43	AM-23	2175826	992384	17	30
13	EN-51	2187602	977682	62	AM-26	2176298	996689	44	AM-24	2175663	993720	18	44
14	EN-52	2189697	977202	58	EN-168	2212719	935460	59	AM-27	2176452	998372	17	29
15	EN-58	2188518	975311	59	NAS-10	2179000	991000	48	AM-28	2176226	1000917	31	15
16	EN-59	2191631	975847	60	NAS-11	2179430	989399	46	EN-12	2178807	994041	31	28
17	EN-65	2189465	973240	57	SW-49	2163000	991000	61	EN-37	2182943	982334	24	36
18	EN-71	2190639	971671	57	SW-64	2163255	974798	57	EN-43	2183857	979307	36	18
19	EN-72	2180746	969609	57	WN-1	2174727	999130	54	EN-57	2186046	975207	31	29
20	EN-73	2182835	969497	59	WN-3	2174072	998005	59	EN-64	2187315	973544	16	29
21	EN-74	2185072	969421	57	WN-4	2176574	998049	54	EN-85	2193287	967129	30	29
22	EN-77	2193749	969878	61	WN-6	2174368	995097	56	EN-95	2195476	964766	37	18
23	EN-78	2196171	969570	60	WN-7	2175329	994002	54	EN-96	2197040	965039	29	30
24	EN-79	2198653	969496	57	WN-8	2177162	995953	56	ENS-02	2218689	960365	46	11
25	EN-80	2181543	967532	57	WN-10	2173927	994125	59	ENS-05	2217787	960001	45	12
26	EN-81	2183705	967460	62	WN-11	2176486	994136	52	GAJ-01	2182342	978471	16	48
27	EN-82	2194314	966784	57	WN-14	2175026	992511	54	GAJ-02	2181503	977557	40	42
28	EN-84	2190314	967199	58	WN-15	2177640	992062	52	GAJ-03	2180689	977050	14	28
29	EN-86	2195022	967723	59	WN-17	2174020	990321	49	GAJ-04	2180514	975304	23	20
30	EN-87	2197459	969362	58	WN-18	2176937	990280	53	GAJ-05	2180833	972897	17	25
31	EN-88	2198531	967566	60	WN-19	2178721	990024	52	GAJ-25	2182197	972407	14	28
32	EN-89	2203256	966714	58	WN-21	2174956	987936	52	GAJ-26	2181200	973200	16	29
33	EN-90	2184631	965544	56	WN-22	2177476	988184	56	GAJ-27	2181500	974800	23	21
34	EN-91	2187101	965306	56	WN-23	2179615	987930	56	GAJ-28	2181215	976480	17	28
35	EN-92	2189426	964963	56	WN-24	2176470	985790	50	GAJ-29	2182396	977666	14	28
36	EN-93	2192042	965116	61	WN-25	2178191	985906	53	JRS-01	2218195	959123	53	53
37	EN-94	2193989	964982	59	WN-26	2180449	985515	55	JRS-02	2217869	958614	50	54
38	EN-97	2200243	965095	56	WN-28	2174528	984413	54	JRS-03	2217787	958001	12	53
39	EN-98	2202859	964630	58	WN-29	2177272	984109	55	JRS-04	2217422	957832	12	47
40	EN-99	2182610	963345	59	WN-30	2181051	983717	52	JRS-05	2217314	957221	48	15
41	EN-100	2187443	963568	56	WN-31	2181745	983370	56	JRS-06	2216819	957105	44	16
42	EN-101	2187746	963524	60	WN-33	2173272	982650	49	JRS-07	2216911	957161	49	13
43	EN-102	2190804	963092	61	WN-34	2175948	982071	52	JRS-08	2216911	956161	49	12
44	EN-103	2192935	962996	64	WN-35	2177940	981862	56	JRS-09	2216889	955608	46	12
45	EN-104	2199146	963378	56	WN-36	2180632	981622	56	JRS-10	2216738	955306	45	12
46	EN-105	2201443	963221	61	WN-39	2174494	979717	56	JRS-11	2216660	954756	42	14
47	EN-106	2204978	963601	57	WN-40	2177185	980141	56	JRS-12	2216515	954608	45	11
48	EN-107	2183860	961476	59	WN-41	2179681	979925	54	JRS-13	2216414	954151	46	12
49	EN-108	2187467	958162	57	WN-42	2181846	979972	58	JRS-14	2216598	953824	38	19
50	EN-109	2189348	960754	63	WN-46	2175872	978170	56	JRS-15	2216079	953426	31	30
51	EN-110	2192118	960837	58	WN-47	2178258	978008	55	JRS-16	2216145	952992	29	31
52	EN-111	2201164	960929	59	WN-48	2175895	978182	57	JRS-17	2216018	952598	14	40
53	EN-112	2203113	961124	59	WN-49	2183336	977429	57	JRS-18	2215828	952021	36	20
54	EN-113	2205351	960940	59	WN-53	2177132	975689	56	JRS-19	2215701	951626	24	31
55	EN-114	2207640	961337	60	WN-54	2179569	975801	53	JRS-21	2215569	951109	24	37
56	EN-115	2186021	959285	59	WN-56	2183723	975871	56	JRS-22	2215406	950500	23	39
57	EN-116	2187709	958945	59	WN-60	2177962	973760	53	JRS-24	2214980	949564	24	34
58	EN-117	2189000	959000	58	WN-62	2182744	973522	53	JRS-25	2214917	949382	39	20
59	EN-118	2193000	959000	59	WN-63	2184894	973414	52	JRS-26	2214931	949043	37	19
60	EN-119	2202064	958538	59	WN-66	2179757	971713	52	JRS-27	2214775	948618	43	14
61	EN-120	2204318	958767	58	WN-67	2181986	971370	52	JRS-28	2214702	948191	45	11
62	EN-121	2207143	958682	58	WN-68	2187249	971360	58	JRS-29	2214381	947804	23	34
63	EN-122	2208888	959317	57	WN-69	2186452	971286	52	JRS-30	2214337	947406	29	29

S. No.	East Nawabshah Tubewells				West Nawabshah Tubewells				Nawabshah Scavenger Tubewells				
	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	QFresh (lps)	QSaline (lps)
64	EN-123	2211594	959053	58	WN-70	2188003	970903	53	JRS-31	2214260	946855	24	37
65	EN-124	2187887	956812	58	WN-75	2187506	969331	58	JRS-32	2214129	946571	23	32
66	EN-125	2189020	957237	58	WN-76	2189475	968988	57	JRS-33	2214154	945958	23	33
67	EN-126	2191711	956939	58	WN-83	2188314	967100	54	JRS-34	2213901	945547	34	17
68	EN-127	2201294	957385	59	WN-169	2164061	1000568	56	JRS-35	2213928	945254	21	38
69	EN-128	2203235	957173	41	WN-170	2166418	1000481	57	JRS-36	2213880	944883	37	17
70	EN-129	2205408	957101	59	WN-171	2170883	996219	54	JRS-37	2214072	944356	0	43
71	EN-130	2207351	956726	57	WN-172	2165121	998351	60	JRS-38	2214093	943921	20	34
72	EN-131	2210081	956152	59	WN-173	2167366	997907	57	JRS-39	2214042	943490	44	12
73	EN-132	2212527	956769	61	WN-174	2163857	996297	57	JRS-40	2214282	943025	29	29
74	EN-133	2187733	955351	57	WN-175	2166224	996361	59	JRS-41	2214177	942712	14	40
75	EN-134	2190390	955543	59	WN-176	2168549	995476	59	JRS-42	2214361	942243	43	11
76	EN-135	2196968	954736	57	WN-177	2170074	985470	53	JRS-43	2214499	941736	45	11
77	EN-136	2199019	954712	57	WN-178	2164762	994690	56	JRS-44	2214350	941548	31	14
78	EN-137	2201464	954794	57	WN-179	2166982	994176	57	JRS-45	2214372	940938	20	34
79	EN-138	2203824	953718	58	WN-180	2170139	994279	53	JRS-46	2214625	940393	37	18
80	EN-139	2206267	954989	59	WN-181	2164187	992279	56	JRS-47	2214879	940170	0	42
81	EN-140	2208725	954679	59	WN-182	2166336	992642	56	JRS-48	2214958	939435	29	29
82	EN-141	2211313	954204	59	WN-183	2168222	992413	59	JRS-49	2215133	938964	35	18
83	EN-142	2189309	952881	64	WN-184	2163150	992842	59	JRS-50	2215286	938415	44	11
84	EN-143	2191160	953160	58	WN-185	2164970	989930	58	JRS-51	2215455	938065	44	16
85	EN-144	2194735	952824	61	WN-186	2166398	990442	57	JRS-52	2215575	937675	28	29
86	EN-145	2195591	952979	60	WN-187	2170376	989045	54	JRS-53	2215839	937185	32	20
87	EN-146	2198112	952904	56	WN-188	2162930	989467	58	JRS-54	2215993	936819	30	30
88	EN-147	2200206	952570	59	WN-189	2163868	988164	55	JRS-55	2216033	936214	28	27
89	EN-148	2202781	952463	62	WN-190	2165686	987991	61	JRS-56	2215869	935815	14	40
90	EN-149	2205352	951691	62	WN-191	2167696	969484	57	JRS-57	2215757	935084	29	27
91	EN-150	2207850	952241	62	WN-192	2161914	987476	59	JRS-58	2215650	934652	29	27
92	EN-151	2209786	952411	59	WN-193	2164274	987346	60	JRS-59	2215551	934191	14	41
93	EN-152	2213069	952379	61	WN-194	2167799	984965	58	JRS-60	2215388	933583	31	28
94	EN-153	2187852	951171	61	WN-195	2162150	984730	60	JRS-61	2215258	933126	14	40
95	EN-154	2190269	950939	59	WN-196	2163586	984207	61	JRS-62	2215130	932701	22	35
96	EN-155	2192484	950689	59	WN-197	2165804	982540	54	JRS-63	2215052	932150	23	37
97	EN-156	2209326	950379	60	WN-198	2168407	983679	59	JRS-64	2214808	931607	29	29
98	EN-157	2211519	950412	56	WN-199	2161980	982257	57	JRS-65	2214682	931243	35	20
99	EN-158	2186324	948526	56	WN-200	2163721	982131	56	JRS-66	2214637	930814	38	20
100	EN-159	2189262	948189	57	WN-201	2168325	982468	56	JRS-67	2214752	930225	42	14
101	EN-160	2210072	948287	59	WN-203	2163362	980556	57	JRS-68	2214600	927862	43	11
102	EN-161	2211853	948399	60	WN-204	2165529	979475	52	JRS-69	2214658	927214	45	14
103	EN-162	2210848	945833	56	WN-205	2168268	979969	57	JRS-70	2214532	926850	37	20
104	EN-163	2211837	943939	59	WN-207	2164266	978454	55	JRS-71	2214612	925975	44	14
105	EN-164	2211776	942090	57	WN-208	2166067	964129	51	JRS-72	2214626	925739	44	15
106	EN-165	2212943	938357	57	WN-209	2166372	973499	58	JRS-73	2214583	925372	43	16
107	EN-166	2214425	935611	57	WN-210	2167979	975863	54	JRS-74	2214674	924876	43	14
108	EN-167	2214173	933982	66	WN-211	2164380	974172	52	JRS-75	2214951	924157	43	14
109	ENS-1	2218689	960365	56	WN-212	2165172	972051	54	JRS-76	2214629	923770	14	40
110	ENS-3	2210719	960042	60	WN-213	2167349	971921	49	JRS-77	2215109	923259	43	14
111	ENS-4	2215117	957980	62	WN-214	2164415	970288	52	JRS-78	2215282	922729	29	27
112	ENS-6	2215197	956014	61	WN-215	2165133	968047	54	JRS-79	2215315	922174	29	28
113	ENS-7	2212994	954628	63	WN-216	2165281	965776	56	NAS-01	2175215	1001306	37	20
114	ENS-8	2215296	954626	57	WN-217	2165744	964328	54	NAS-02	2175269	1000842	42	14
115	ENS-9	2214670	952191	61	WN-218	2167791	964557	58	NAS-03	2175932	999243	22	35
116	ENS-10	2213808	950780	62	WN-219	2171000	963000	56	NAS-04	2177503	997621	30	28
117	ENS-11	2213181	948314	59	WN-220	2168245	962587	55	NAS-05	2177495	996917	24	37
118	ENS-12	2213405	946305	60	WN-221	2167006	962220	57	NAS-06	2177916	995169	38	21
119	ENS-13	2213258	944066	60	WN-222	2170689	961433	61	NAS-07	2177947	994217	43	15
120	GAJ-6	2180608	971522	42	WN-223	2172789	961636	52	NAS-08	2178327	993112	23	35
121	GAJ-7	2180950	970400	46	WN-224	2168059	960257	56	NAS-09	2178403	991865	31	33
122	GAJ-8	2181087	968579	45	WN-225	2169658	959417	60	NAS-12	2179788	988658	39	20
123	GAJ-9	2181365	967050	42	WN-226	2171729	959846	57	NAS-13	2180335	987360	36	19
124	GAJ-10	2182265	964409	43	WN-227	2172101	959796	59	NAS-14	2180759	986028	31	28
125	GAJ-11	2185237	963847	41	WN-228	2167000	959000	59	NAS-15	2180962	985296	29	30
126	GAJ-12	2184243	960690	42	WN-229	2170788	957814	61	NAS-16	2181627	984154	36	20
127	GAJ-13	2184643	959043	37	WN-230	2172774	957179	64	NAS-17	2182055	982388	28	28
128	GAJ-14	2184989	958043	44	WN-231	2172530	955987	62	NAS-18	2182450	980774	35	19

S. No.	East Nawabshah Tubewells				West Nawabshah Tubewells				Nawabshah Scavenger Tubewells				
	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	Q (lps)	Tubewell No.	Northing (m)	Easting (m)	QFresh (lps)	QSaline (lps)
129	GAJ-15	2185557	955773	45	WN-232	2174120	955357	56	NAS-19	2182901	979669	36	18
130	GAJ-16	2187000	953000	44	WN-233	2176839	955389	57	NAS-20	2183424	980455	37	17
131	GAJ-17	2186791	955370	46	WN-241	2180465	962077	57	NAS-21	2183029	981558	37	20
132	GAJ-18	2186124	958016	44					NAS-22	2182627	983142	37	20
133	GAJ-19	2185568	960572	39					NAS-23	2182379	983934	45	14
134	GAJ-20	2184954	962413	44					NAS-24	2182048	984939	36	20
135	GAJ-21	2183784	964589	45					NAS-25	2181820	985936	36	20
136	GAJ-22	2183108	966403	44					NAS-26	2181374	986952	40	19
137	GAJ-23	2185024	967530	46					NAS-27	2180917	988030	45	12
138	GAJ-24	2182197	972407	43					NAS-28	2180345	988984	45	12
139	JAM-20	2215159	951248	58					NAS-29	2179929	990190	30	28
140	JAM-23	2214675	950253	56					NAS-30	2179346	991474	42	14
141	JAM-65	2214342	929718	63					NAS-31	2179045	992628	46	12
142	JAM-66	2213810	928866	57					NAS-32	2178733	994882	42	15
143	JAM-67	2214270	928971	63					NAS-33	2178631	995898	42	14
144	JAM-68	2214189	928002	63					NAS-34	2178388	996807	46	12
145	EN-A 01	2219000	960050	57					NAS-35	2177870	997919	23	32
146									NAS-36	2177678	998595	14	40
147									NAS-37	2177235	999577	45	11
148									NAS-38	2176328	1000282	40	22
149									NAS-39	2176227	1001443	45	15
150									NAS-40	2183342	978545	29	15
151									NAS-41	2183889	977026	31	16
152									NAS-42	2184621	975752	29	14
153									NAS-43	2185835	974232	15	31
154									NAS-44	2187011	972850	23	20
155									NAS-45	2188085	971736	22	20
156									NAS-46	2188862	970402	30	14
157									NAS-47	2190143	969052	0	42
158									NAS-48	2190909	967974	22	29
159									NAS-49	2192043	966818	25	19
160									NAS-50	2193682	966257	24	22
161									NAS-51	2194654	965631	22	20
162									NAS-52	2196819	964408	14	28
163									NAS-53	2198255	963010	15	29
164									NAS-54	2198820	961346	16	30
165									NAS-55	2199099	959938	14	28
166									NAS-56	2199971	956312	17	31
167									NAS-57	2200358	955548	14	29
168									NAS-58	2199853	958738	16	27
169									NAS-59	2199629	961479	17	29
170									NAS-60	2198979	962315	22	20
171									NAS-61	2198244	963893	17	28
172									NAS-62	2199849	959439	17	28
173									NAS-63	2196277	965415	31	16
174									NAS-64	2195378	965785	17	29
175									NAS-65	2194314	966784	31	15
176									NAS-66	2191929	967718	29	14
177									NAS-67	2190903	968743	29	14
178									NAS-68	2190036	970063	31	14
179									NAS-69	2188825	971419	23	20
180									NAS-70	2187807	972554	29	12
181									NAS-71	2186500	974050	24	20
182									NAS-72	2185501	975810	30	16
183									NAS-73	2185176	976639	30	14
184									NAS-74	2184160	978175	29	13
185									WN-55	2180986	975792	25	35
186									WN-61	2180557	974133	24	35
187									WN-236	2177840	953076	30	29
188									WN-238	2177982	951675	0	29
189									WN-240	2180041	949113	28	30

Table B. Salient Features of the Rohri, Amurji, Gajrah, Ali Bahar, Jam, and Nasrat Systems for River Package.

	Bed	Bed	Full Supply	
RD	Width	Level	Level	
(1000 m)	BW (m)	BL (m)	FSL (m)	
Rohri Main Canal (RD 100-246 km)				
99.970	62.48	43.11	46.77	Kandiaro X-Regulator
129.229	53.34	40.74	44.40	Naushero Feroze X-
129.229	49.38	40.43	44.09	
134.715	49.22	40.03	43.69	Phull Fall Regulator
134.715	49.22	38.97	42.62	
150.869	48.77	37.81	41.46	Yousuf Dahri X-Regulator
150.869	46.02	35.82	39.48	
159.403	45.41	35.24	38.89	Duro Fall X-Regulator
159.403	45.41	33.86	37.52	
176.166	44.80	32.65	36.31	Jamalshah X-Regulator
176.166	43.43	32.65	36.31	
179.214	43.43	32.42	36.08	Mirza Bagh X-Regulator
179.214	43.43	31.20	34.86	
188.052	43.13	30.72	34.38	Chanesar X-Regulator
188.052	41.91	30.72	34.38	
196.891	41.60	30.07	33.73	Sakrand X-Regulator
196.891	40.38	29.16	32.81	
214.874	39.77	27.86	31.51	Kumblima X-Regulator
214.874	36.27	26.58	29.99	
233.161	35.66	25.05	28.47	Zerpir X-Regulator
233.161	35.51	24.44	27.86	
245.962	32.46	23.42	26.80	Kambdaro X-Regulator

	Bed	Bed	Full Supply	
RD	Width	Level	Level	
(1000 m)	BW (m)	BL (m)	FSL (m)	
Amurji Branch (+James & Nawabshah Distributaries)				
0.000	13.26	38.90	40.61	Darya Khan X-Regulator
24.749	10.06	36.33	37.79	
24.749	10.06	36.37	37.56	Daur Regulator
40.232	6.10	33.22	34.14	
40.232	3.96	33.04	33.89	51000 X-Regulator
53.231	1.37	32.92	33.53	
Gajrah Branch (+Chan Babu				
0.000	6.86	34.56	36.24	Gajrah Head Regulator
27.857	7.24	29.72	30.71	
27.857	7.24	29.72	30.71	Nawabshah X-Regulator
52.850	3.05	29.26	30.17	
Ali Bahar Branch (+Lundo Distributary)				
0.000	11.73	29.90	31.42	Ali Bahar Head
6.370	11.12	28.45	29.50	
6.370	7.92	28.43	29.49	Lundo Head Regulator
28.119	7.62	23.32	23.90	
Jam Branch (+Berani Distributary)				
0.000	10.97	26.09	27.49	Jam Head Regulator
24.444	7.62	23.35	24.44	
24.444	7.01	23.44	24.42	Berani Head Regulator
33.846	6.71	21.60	22.49	
Nasrat Branch (+Channa & Shahpur Distributaries)				
0.000	19.66	43.13	45.87	Nasrat Head Regulator
96.343	10.00	28.19	29.81	
96.343	8.08	28.07	29.38	Channa Head Regulator
114.020	6.10	25.77	26.91	
114.020	5.64	25.69	26.76	Shahpur Head Regulator
130.875	4.57	25.30	25.91	

Table B (contd.). Salient Features of the Jamrao System for River Package.

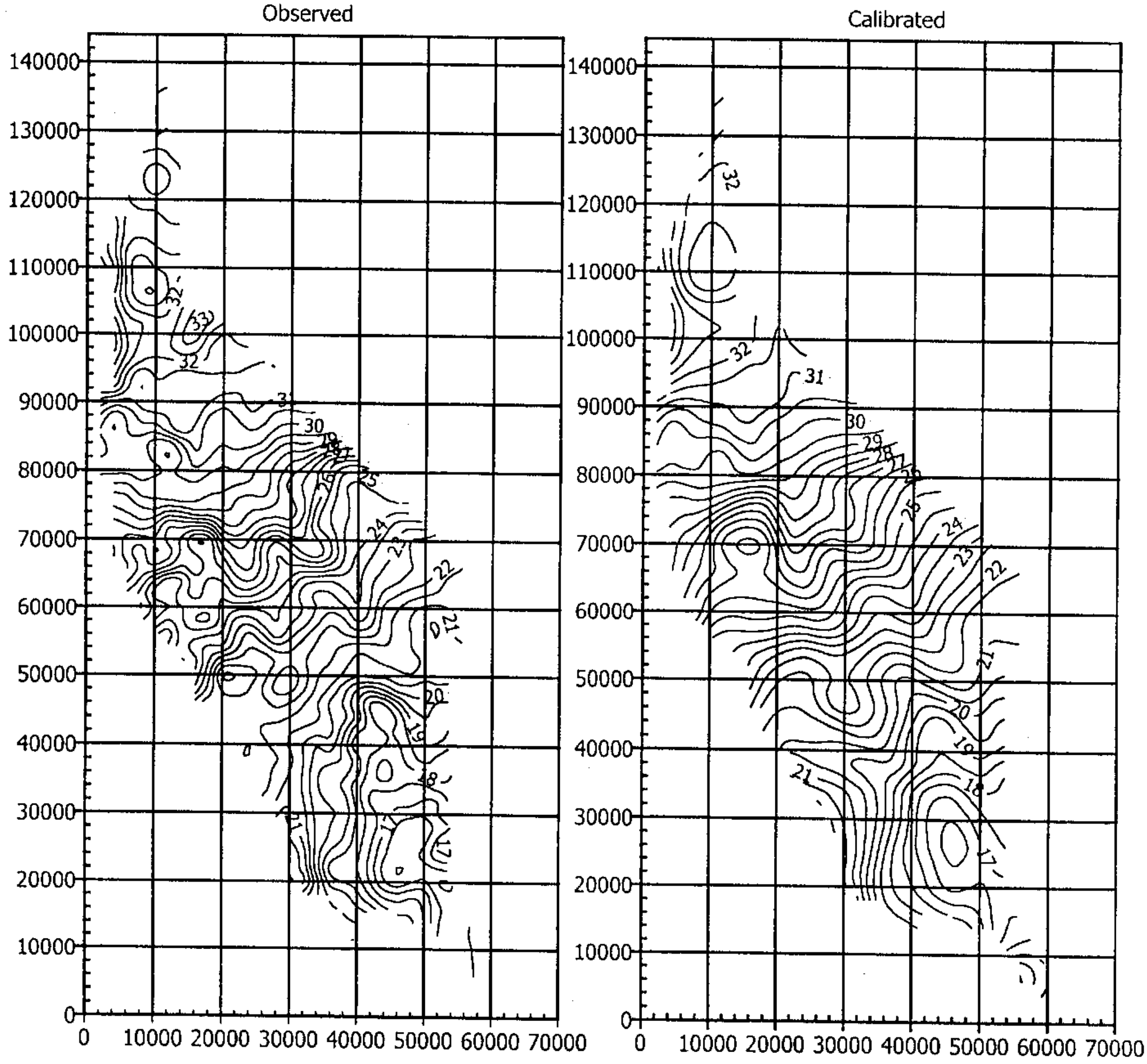
	Bed	Bed	Full Supply	
RD	Width	Level	Level	
(1000 m)	BW (m)	BL (m)	FSL (m)	
Jamrao Canal (RD 14.95 to 81.1 km)				
14.950	43.85	29.30	31.63	
17.522	43.00	29.04	31.36	Jam Sahib Minor
18.482	41.88	28.69	31.00	
20.402	41.03	28.42	30.73	
22.047	39.91	28.07	30.37	
23.830	38.78	27.72	30.01	
25.750	37.66	27.36	29.66	
26.979	38.36	27.04	29.36	17th Mile X-Regulator
28.054	41.30	26.87	29.16	
30.204	42.98	26.67	28.92	
32.355	42.21	26.30	28.62	
34.505	41.30	26.02	28.32	
36.348	42.52	25.80	28.04	
38.498	43.13	25.52	27.77	
40.649	42.37	25.19	27.47	
43.260	41.61	24.80	27.14	Mahi Minor
45.257	39.93	24.40	26.82	Rind Minor
47.216	40.39	24.18	26.54	
49.828	40.69	23.79	26.23	32nd Mile X-Regulator
51.600	39.32	23.41	25.96	
53.667	39.32	23.27	25.77	
55.144	39.62	23.19	25.61	
57.211	39.62	23.07	25.46	Duthro Minor
59.279	40.54	22.82	25.26	
61.346	41.30	22.60	25.06	
63.413	40.39	22.42	24.89	
64.890	40.39	22.26	24.73	
67.252	41.15	22.08	24.53	
69.024	40.39	21.91	24.33	
71.387	39.01	21.69	24.13	
72.568	38.25	21.51	23.96	Dalore Distributary
73.602	35.81	21.39	23.82	49th Mile X-Regulator
75.542	35.05	21.24	23.65	
78.408	35.53	21.10	23.42	
78.707	34.42	21.00	23.27	
81.096	33.93	20.90	23.15	

Table C. List of Distributaries and Minors in the Model Area.

S. No.			Name	Off-take			Design		Outlets	
				RD (km)	GCA (Ha)	CCA (Ha)	Discharge (m 3/sec)	Length (km)	Total (No)	Discharge (m 3/sec)
			Rohri Canal	-	19614	18779	399.31	316.52	55	4.13
1	1		Kandiaro Mr	99.97	1220	1220	0.24	3.66	7	0.22
2	2		Phul Dy	129.53	8289	8204	1.84	24.99	32	1.65
3	3		Bhirya Dy	145.99	3721	3684	2.71	14.51	-	2.38
4		a	Khahi Qasim Mr	5.49	6451	6379	1.49	17.46	-	-
5	4		Manharo Mr	151.17	7511	7331	1.32	12.65	28	1.21
6	5		San Mr	151.17	-	-	-	-	-	-
7	6		James Mr	169.16	3337	3078	0.56	7.01	11	0.50
8	7		Jan Muhammad Mr	176.17	1210	1049	0.14	2.44	4	0.13
9	8		Varayam Mr	176.17	2585	2093	0.39	8.53	6	0.35
10	9		Bilawal Zardari Mr	187.44	4024	3693	0.85	10.94	-	-
11	10		Khairshah Mr	196.89	2414	2255	0.49	5.33	12	0.47
12	11		Khadhro Dy	197.20	11156	10121	2.94	25.60	48	2.35
13		a	Jam Dahri Mr	10.03	1685	1575	0.51	4.72	8	0.46
14	12		Kumblima Mr	214.87	1084	1064	0.20	3.35	8	0.15
15	13		Ali Bahar Branch	214.87	1339	1298	6.43	6.25	7	0.53
16		a	Serhari Mr	6.22	4732	4610	1.02	16.31	25	0.91
17		b	Odhiano Dy	6.22	9300	9083	2.20	19.96	38	1.83
18		c	Lundo Dy	6.22	12880	12677	2.90	30.78	54	2.58
19	14		Khutiro Dy	214.87	2434	2393	0.57	12.80	16	0.42
20	15		Berandi Mr	231.03	4674	4616	0.80	10.06	17	0.67
21	16		Maldasi Mr	242.30	362	3557	0.78	6.25	13	0.68
22	17		Shahdadpur Dy	246.27	5705	5569	1.34	17.37	26	1.21
			Nasrat Branch	99.97	13195	12685	55.22	96.34	56	2.52
23	1		Jalbani Mr	6.86	3916	3885	1.33	13.64	-	-
24	2		Chaheen Mr	21.07	2227	2222	0.51	5.85	-	-
25	3		Drakhi Mr	26.92	855	851	0.20	2.07	-	-
26	4		Chiho Mr	30.20	2566	2561	0.57	4.42	-	-
27	5		Tetri Mr	36.70	3427	3364	0.58	6.92	-	-
28	6		Chanari Mr	39.01	3873	3850	1.26	11.64	-	-
29		a	Sher Khan Mr	5.24	3022	3015	0.42	6.10	-	-
30	7		Khipro Mr	47.09	6070	4966	0.78	7.62	14	0.71
31	8		Left Jari Dy	47.09	3008	2747	0.59	12.50	12	0.53
32	9		Right Jari Dy	47.09	5367	5013	1.15	20.42	18	1.04
33	10		Setharki Dy	47.09	24253	13901	4.14	37.64	55	3.79
34		a	Khariro Mr	24.46	2086	1364	0.35	3.20	6	0.31
35	11		Shinar Mr	65.22	1947	1824	0.24	3.66	6	0.22
36	12		Dhoro Khunjan Mr	67.21	1425	1257	1.67	4.08	-	-
37		a	Akdoi Mr	0.91	4145	3396	0.77	11.12	-	-
38	13		Mianjher Mr	67.21	2123	1947	0.65	5.06	-	-
39	14		Bhit Maru Dy	76.91	6001	5584	2.52	12.58	-	-
40		a	Dewanabad Mr	3.81	1758	1717	0.35	5.63	-	-

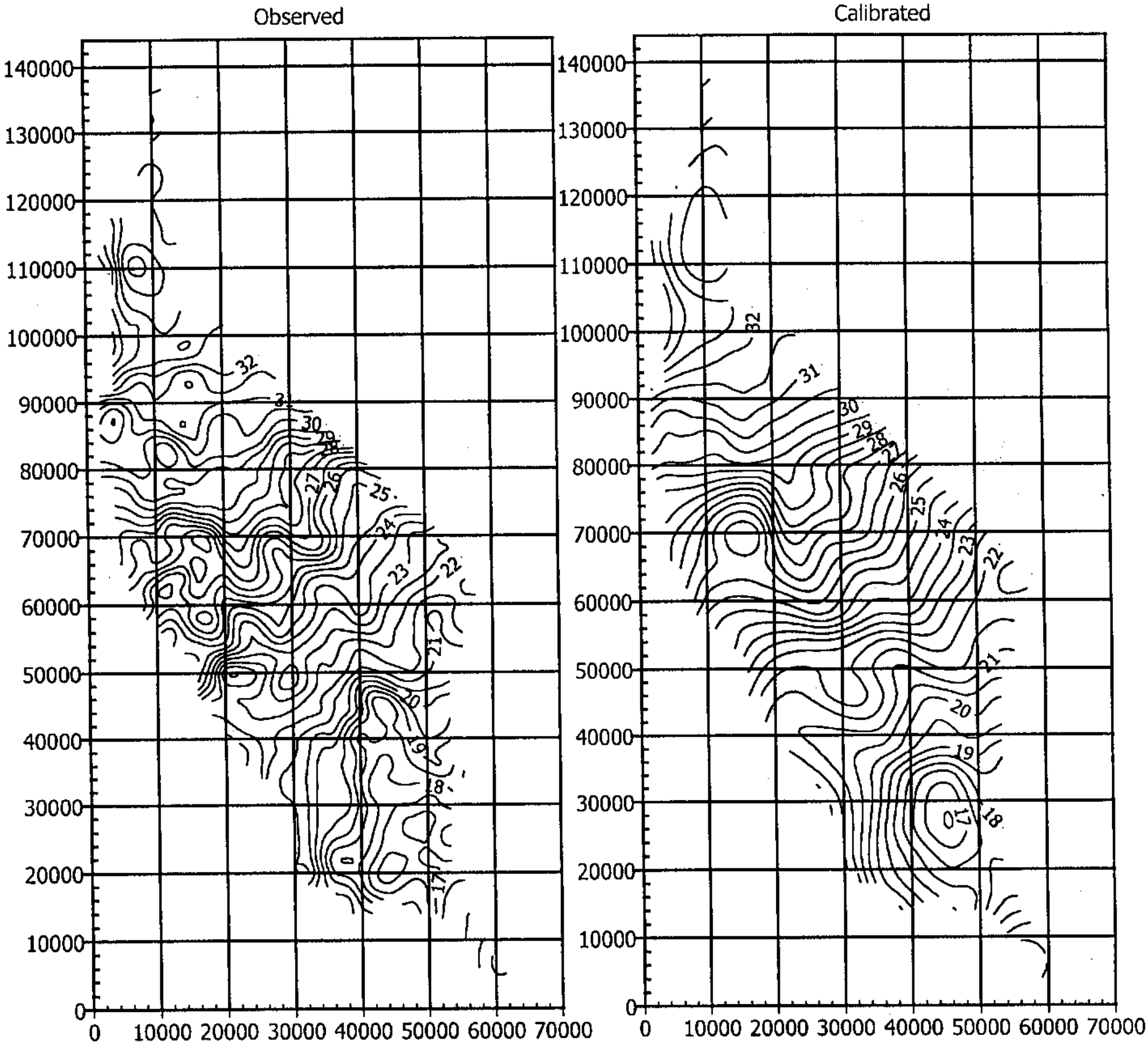
S. No.			Name	Off-take			Design		Outlets	
				RD (km)	GCA (Ha)	CCA (Ha)	Discharge (m 3/sec)	Length (km)	Total (No)	Discharge (m 3/sec)
41	15		Dhoji Mr	76.91	4148	3412	0.88	9.26	-	-
42		a	Suhelo Mr	6.10	2144	1584	0.29	3.95	-	-
43	16		Visro Mr	89:76	2061	1935	0.52	3.55	-	-
44	17		Jam Sahib Dy	89.91	9225	8101	1.63	19.35	33	1.47
45	18		Chan Bandhni Mr	96.46	6391	5997	1.52	17.53	30	1.37
46	19		Shah Hussain Mr	96.46	1671	1639	0.31	2.44	5	0.28
47	20		Gubchani Mr	96.46	783	724	0.68	4.88	3	0.09
48		a	Obhahi Chan Mr	4.88	2942	2763	0.59	6.64	-	-
49	21		Channa Dy	96.46	4963	4644	5.46	17.68	21	1.00
50		a	Gabri Mr	5.43	694	667	0.21	2.04	-	-
51		b	Chamro Mr	17.68	889	859	0.19	0.47	-	-
52		c	Rino Mr	17.68	3628	3451	0.90	7.31	16	0.81
53		d	Shahpur Dy	17.68	12047	11369	3.11	23.77	47	2.31
54			Barhoon Mr	6.86	2078	1961	0.53	4.27	10	0.48
			Amurji Branch	41.94	9322	7505	9.76	24.69	30	1.63
55	1		A. Hussain Mr	18.67	4532	4163	0.88	11.58	16	0.79
56	2		New Daur Mr	18.20	1580	1580	0.40	5.66	-	-
57	3		Farmabad Mr	20.76	1418	1286	0.37	4.11	6	0.33
58	4		Dholu Mr	24.75	7260	5560	1.29	14.93	23	1.17
59	5		James Dy	24.75	8579	8047	4.88	15.39	25	1.42
60		a	Bhamboo Mr	12.07	2322	2057	0.29	1.51	-	-
61		b	Labjiwai Mr	15.54	3392	3105	1.01	8.53	18	0.76
62			Gober Mr	2.68	1059	959	0.24	3.96	5	0.22
63		c	Nawabshah Dy	15.54	3949	3398	1.51	10.97	18	0.74
64			Mangsi Mr	8.53	2944	2777	0.64	9.60	16	0.57
			Gajrah Branch	66.44	5652	5173	10.13	27.89	27	1.08
65	1		Daro Mr	4.72	700	617	0.17	0.76	2	0.15
66	2		Kandi Mr	4.72	1611	1501	0.82	5.18	7	0.44
67		a	Sardarabad Mr	5.15	1756	1613	0.41	6.80	-	-
68	3		Chodiko Mr	16.31	4565	4313	1.23	10.97	13	0.91
69		a	Jam Leghari Mr	3.96	1479	1357	0.35	4.57	6	0.31
70	4		Dago Mr	16.31	898	795	0.33	4.88	4	0.30
71	5		Kiranjhoro Mr	16.31	951	871	0.19	3.35	3	0.17
72	6		Dhoro Naro Mr	27.86	6485	5782	1.46	9.75	23	1.32
73	7		Khiaryoon Mr	27.74	2913	2902	0.62	7.01	13	0.56
74	8		Chanbabu Dy	27.80	11318	10505	3.81	29.11	51	2.63
75		a	Panju Chan Mr	3.66	1340	1282	0.26	4.42	8	0.24
76		b	Jhimal Mr	8.72	4477	4085	1.00	12.04	19	0.90
77		c	Nawaz Dahiri Mr	8.72	887	810	0.31	4.11	5	0.28
			Jam Branch	246.27	4628	4572	8.86	21.33	16	1.44
78	1		Bhobar Dy	19.81	4503	4461	1.01	10.82	16	0.94
79	2		Berani Dy	21.37	3592	3555	3.44	12.50	5	2.95

ANNEXURE II
FIGURES



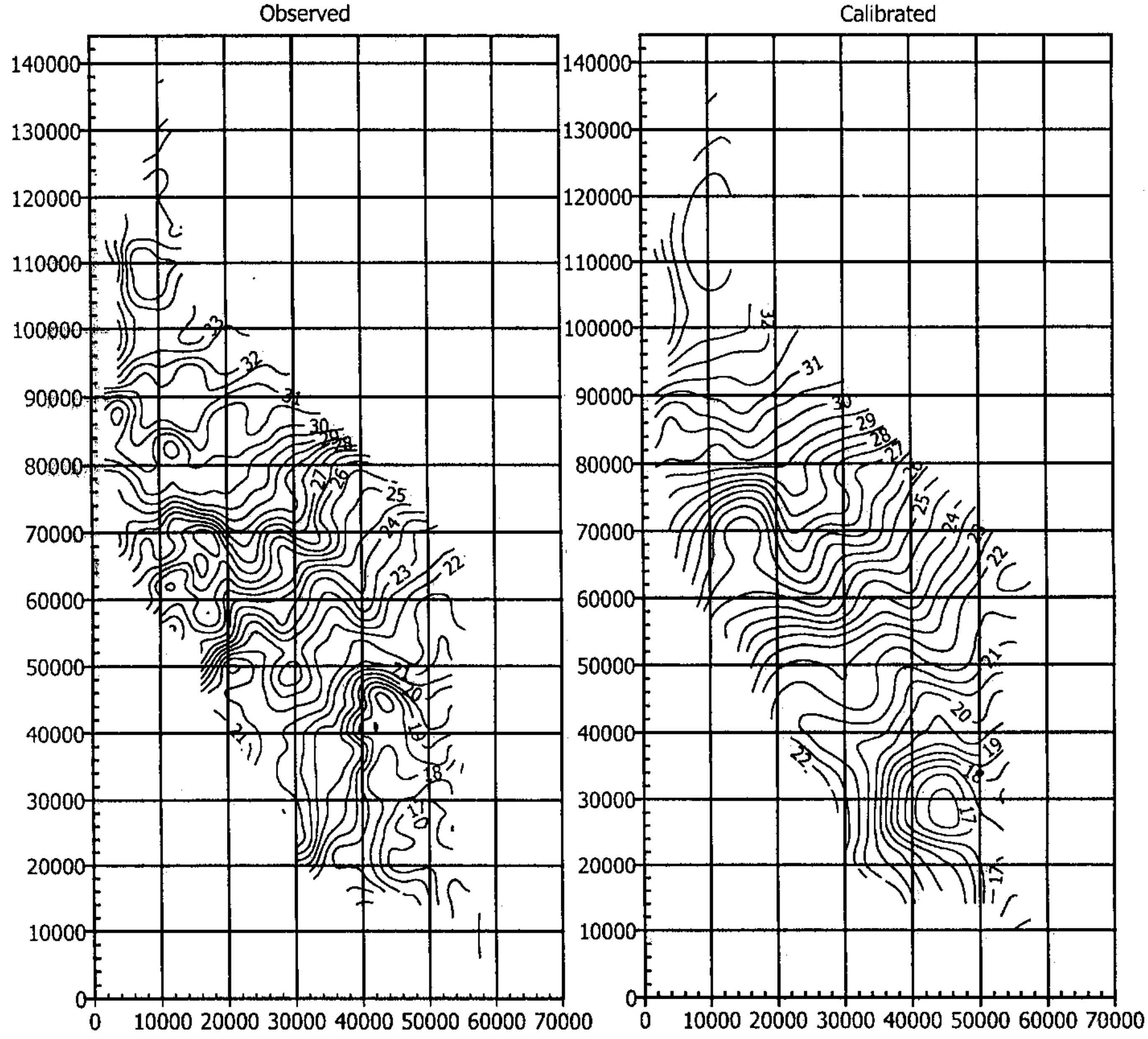
October 1988

Figure II.1. **Observed and Calibrated Water Level Contours, October 1988.**



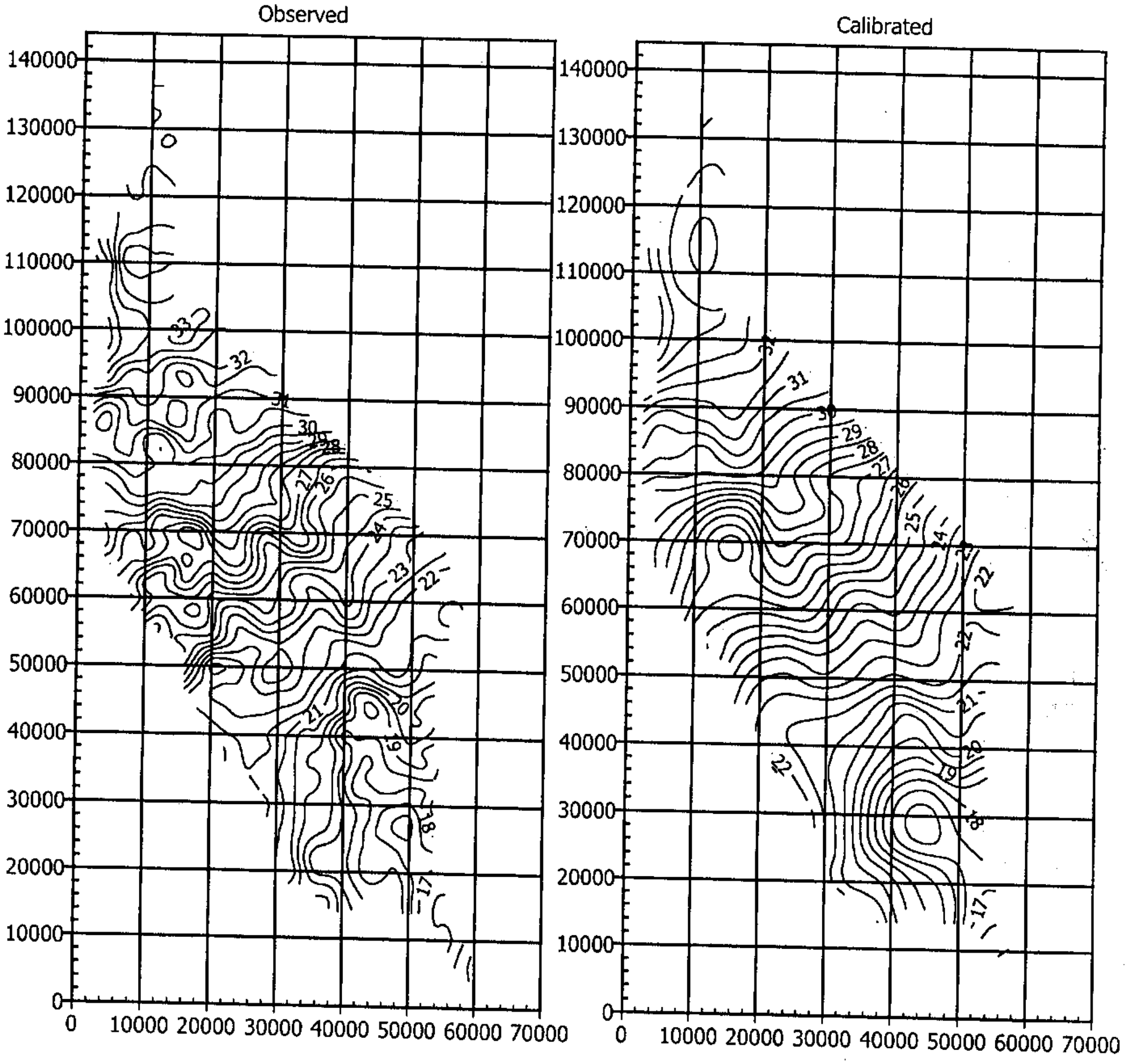
April 1989

Figure II.2. Observed and Calibrated Water Level Contours, April 1989.



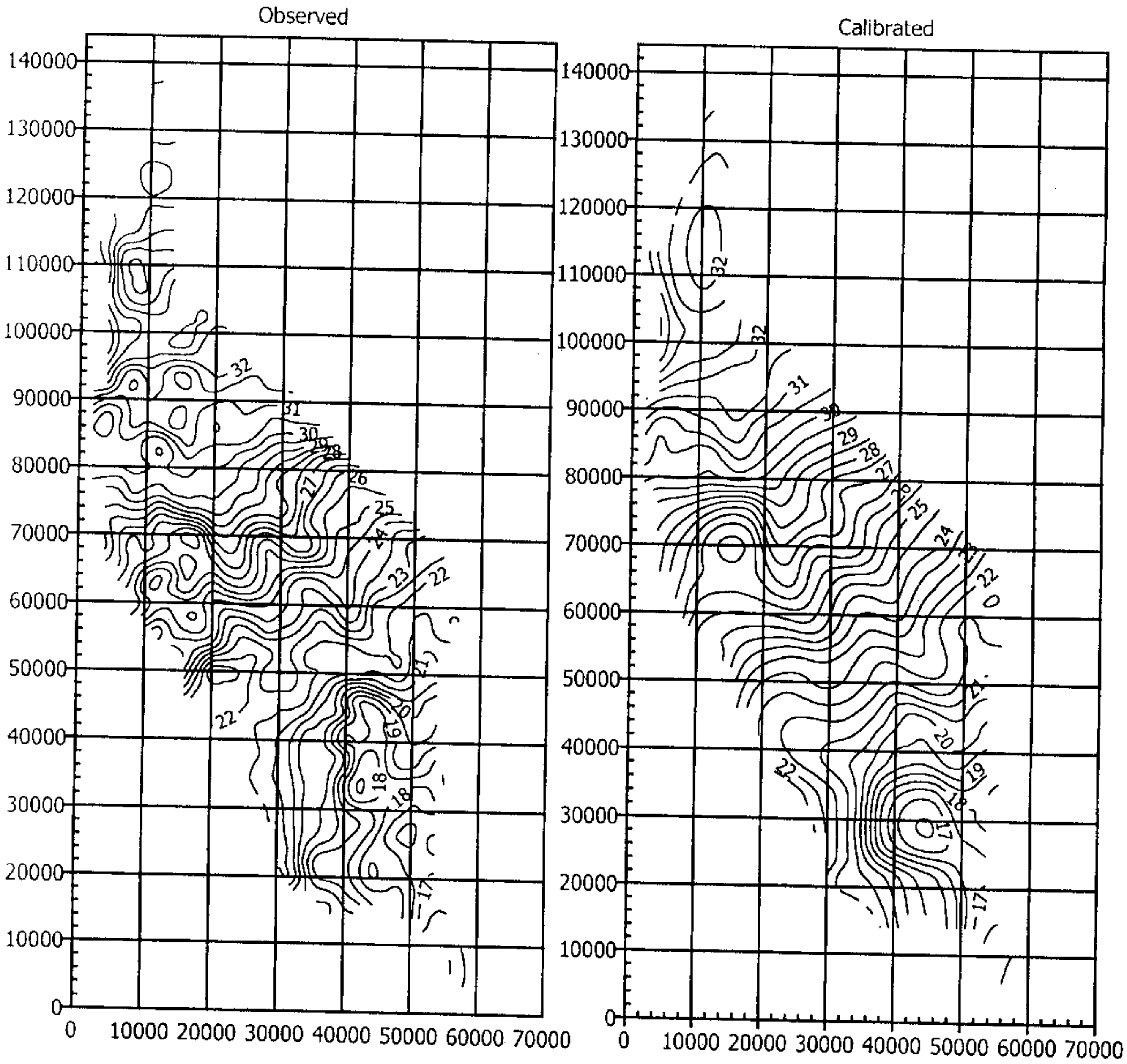
October 1989

Figure II.3. **Observed and Calibrated Water Level Contours, October 1989.**



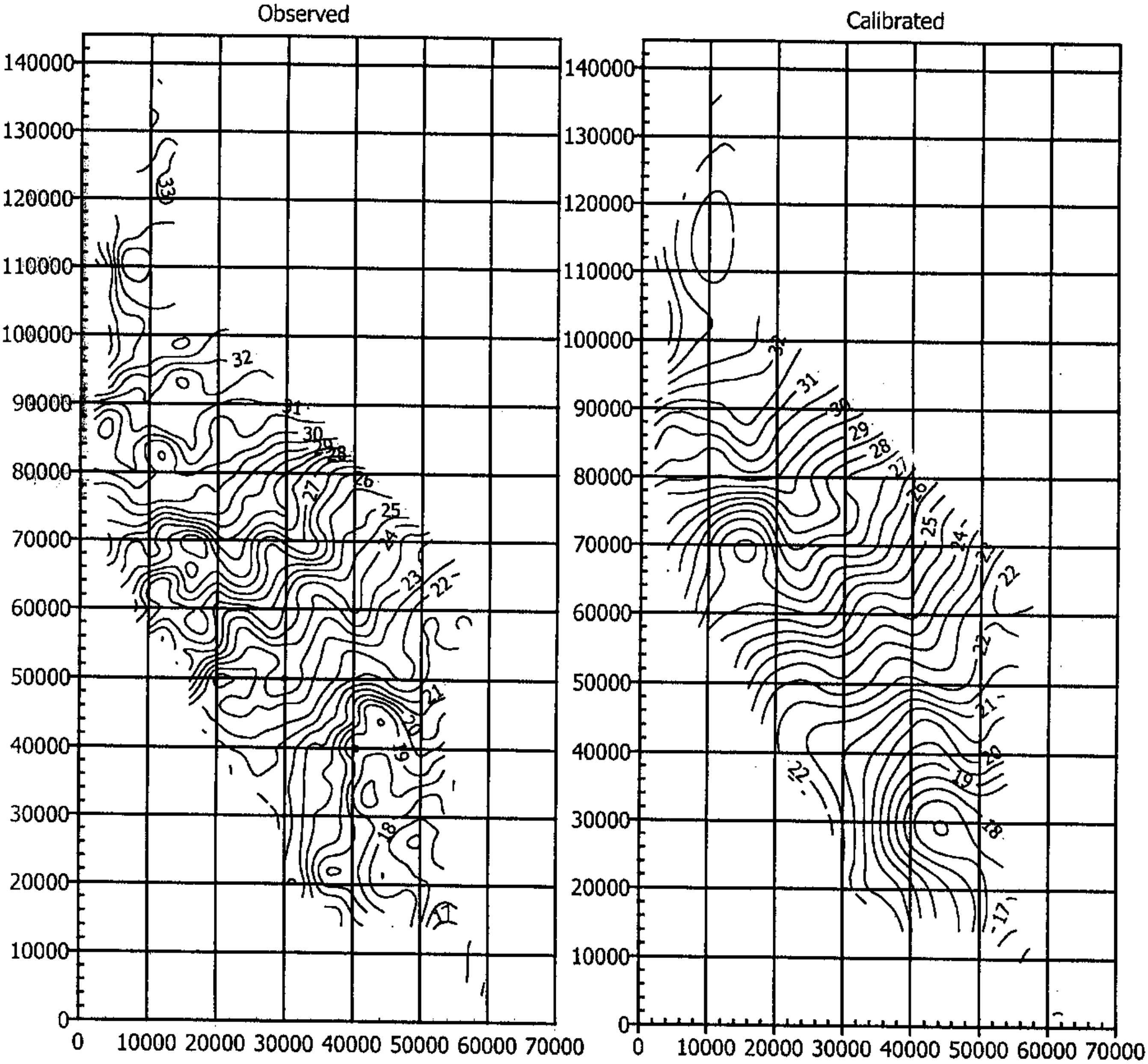
April 1990

Figure II.4. **Observed and Calibrated Water Level Contours, April 1990.**



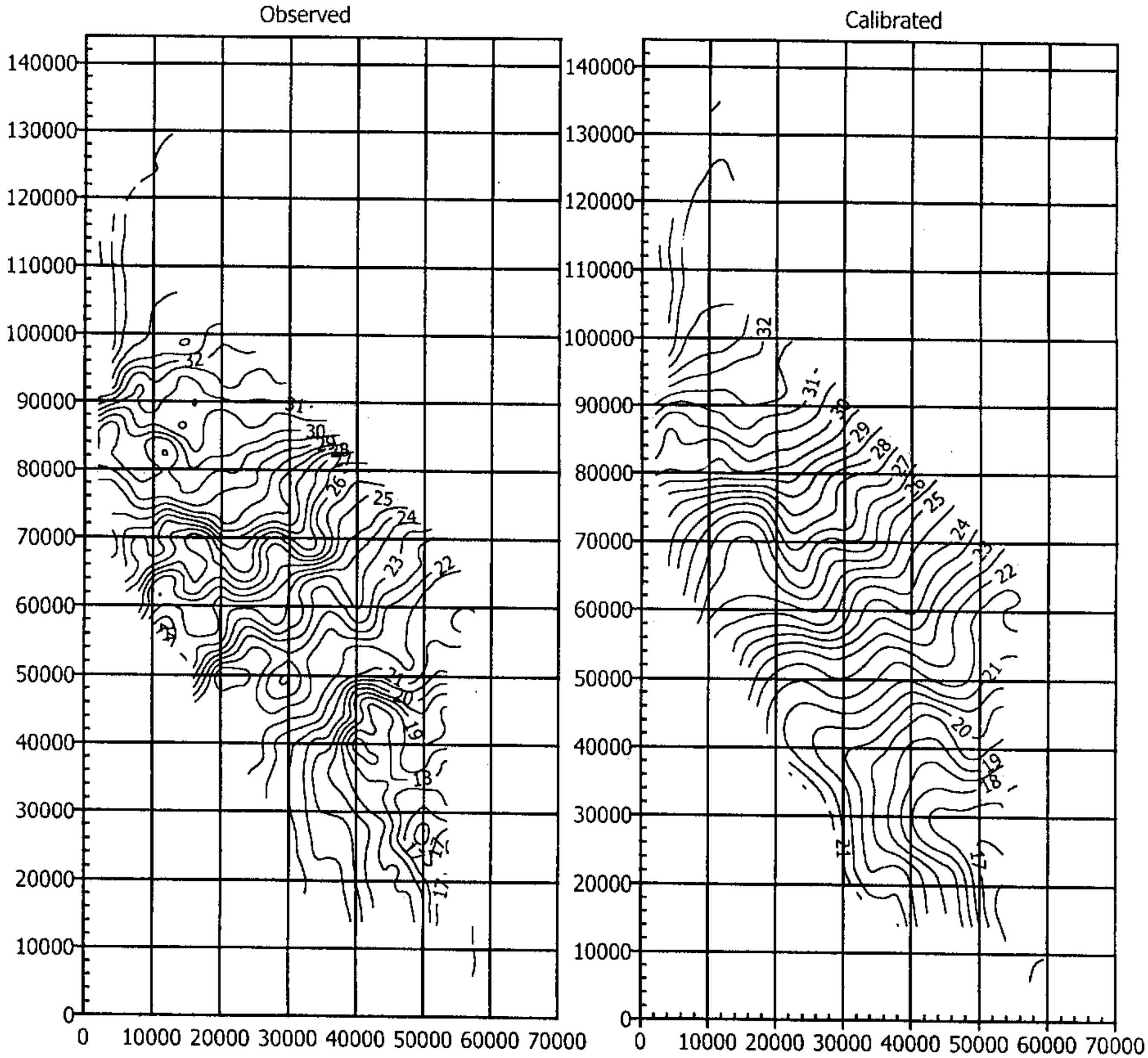
October 1990

Figure II.5. Observed and Calibrated Water Level Contours, October 1990.



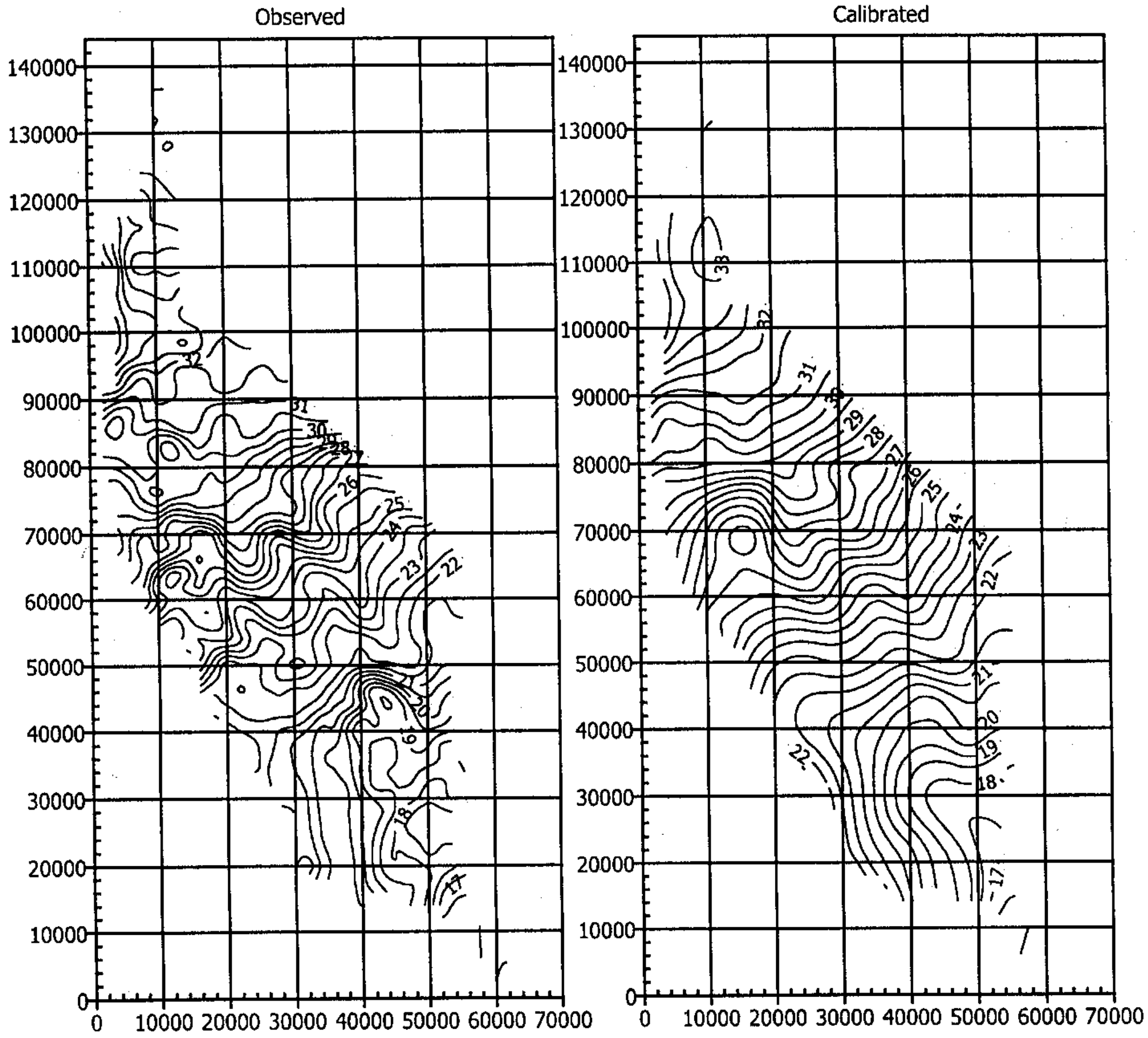
April 1991

Figure II.6. Observed and Calibrated Water Level Contours, April 1991.



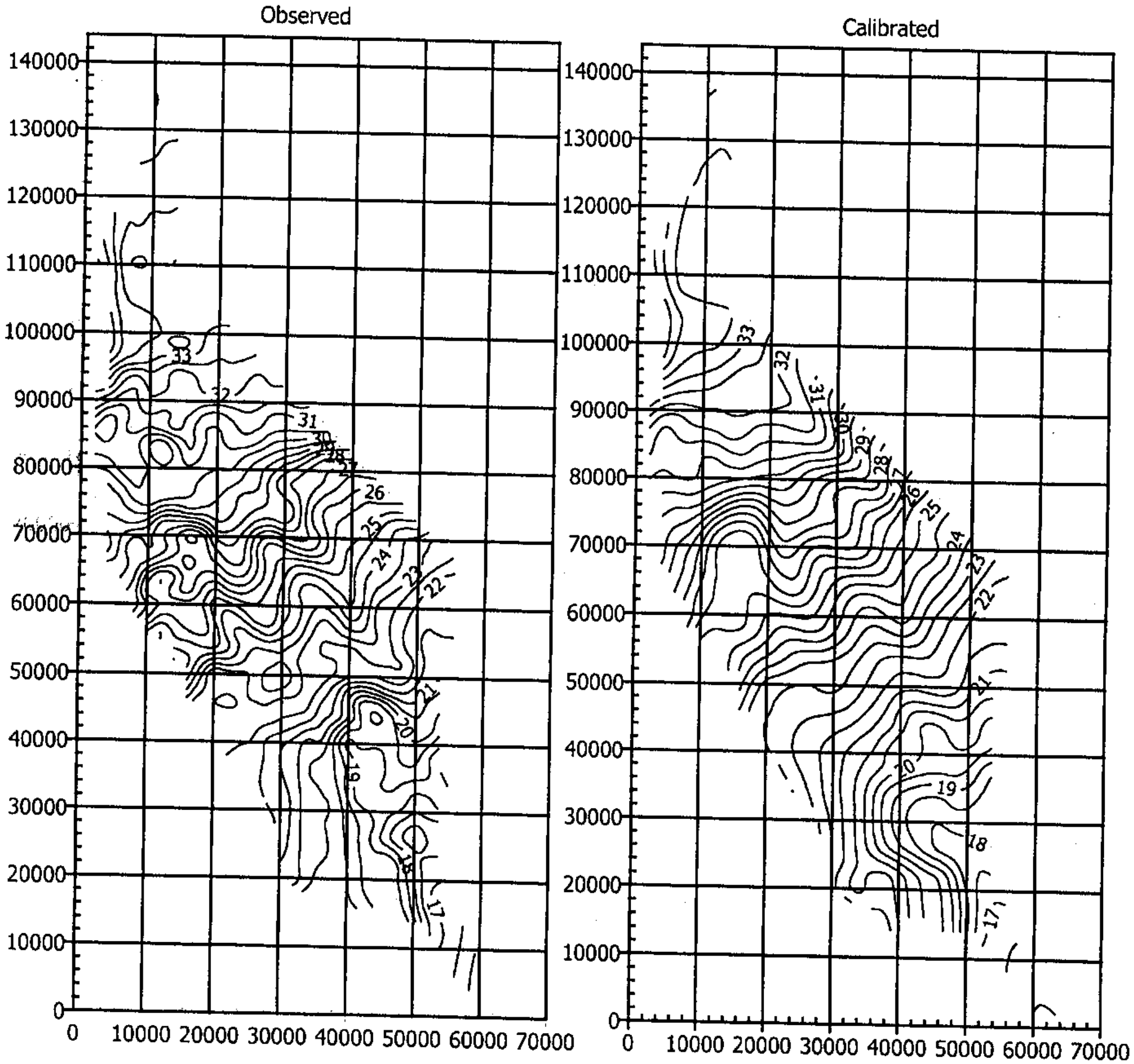
October 1991

Figure II.7. Observed and Calibrated Water Level Contours, October 1991.



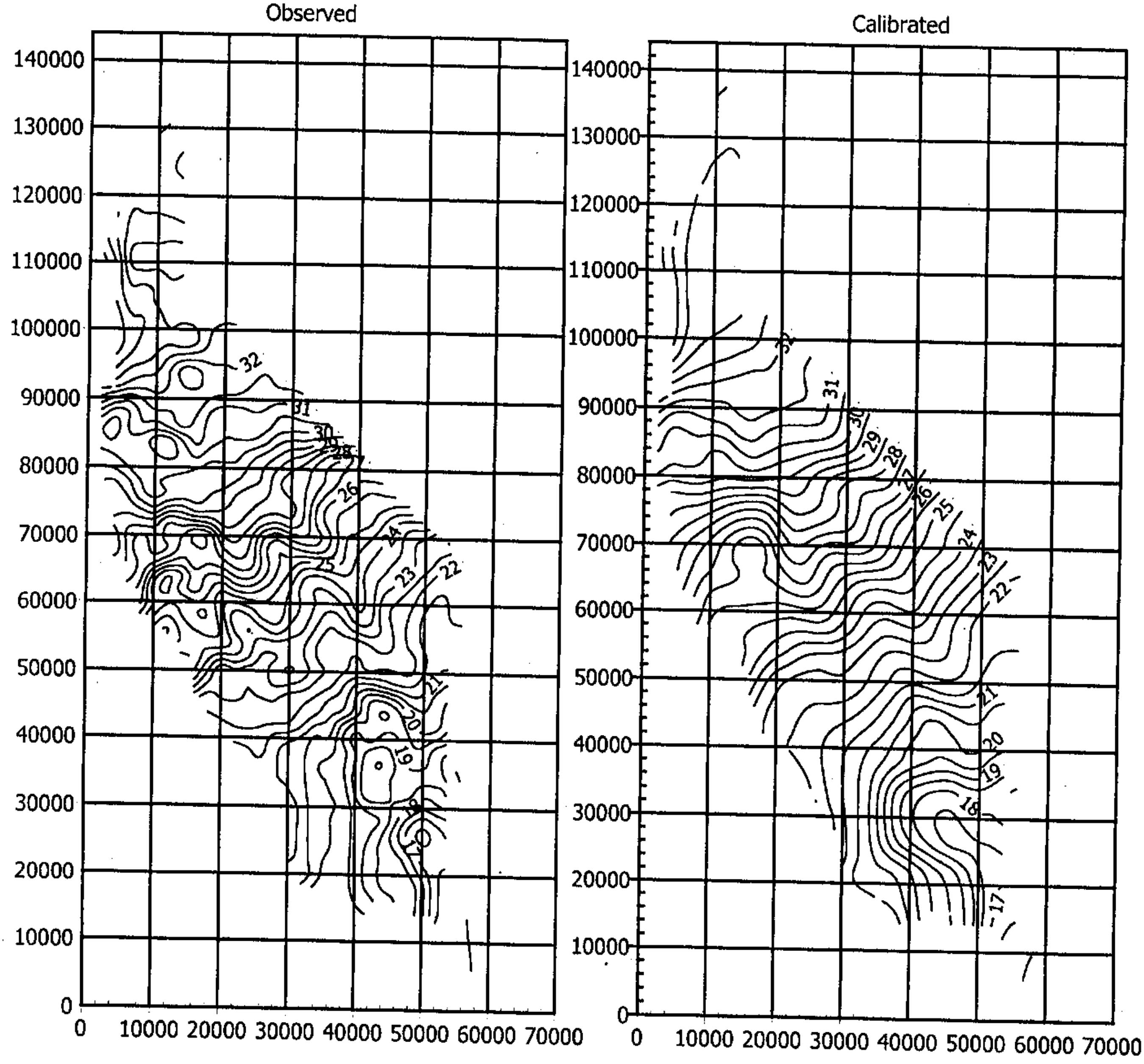
April 1992

Figure II.8. Observed and Calibrated Water Level Contours, April 1992.



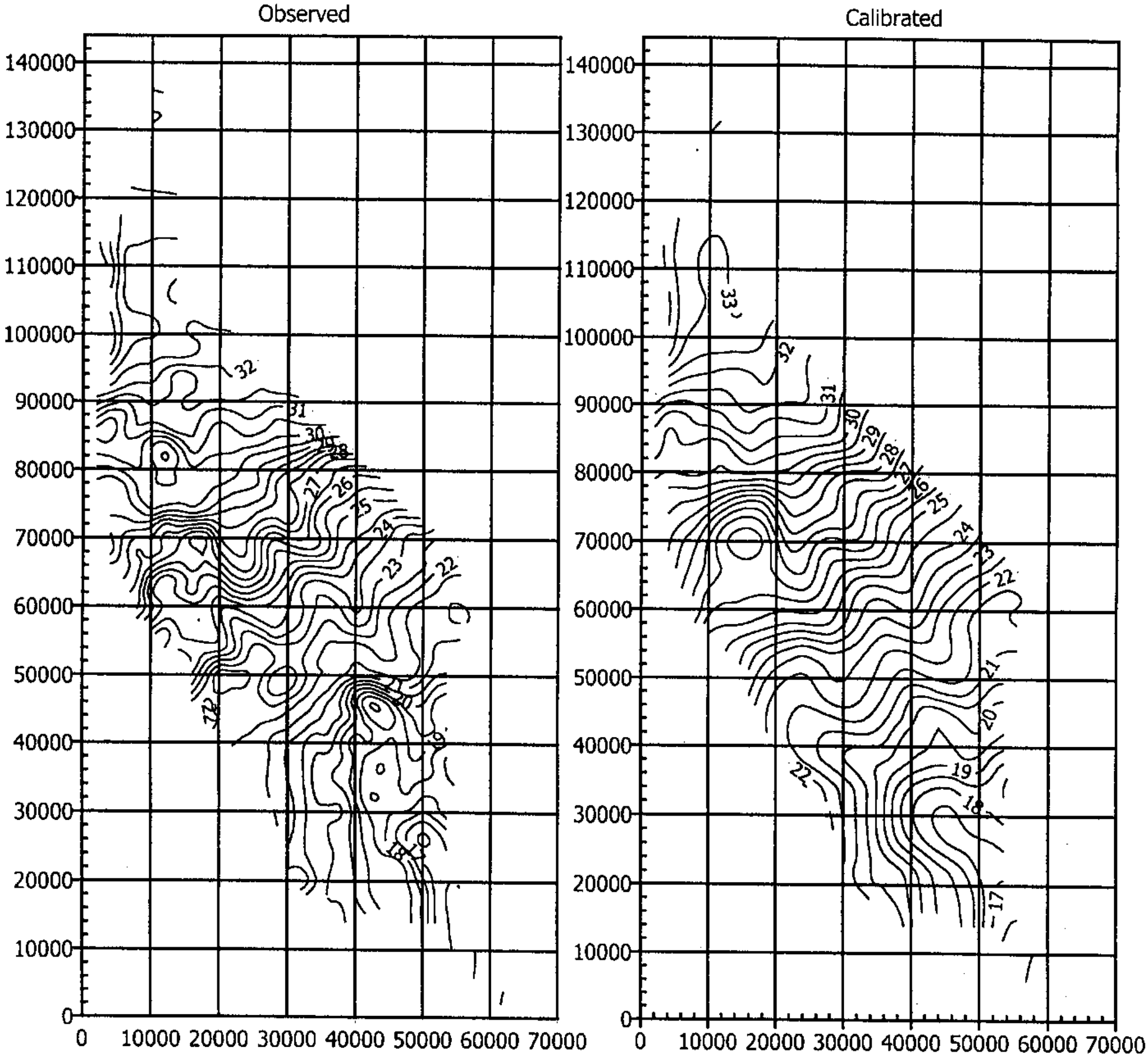
October 1992

Figure II.9. Observed and Calibrated Water Level Contours, October 1991.



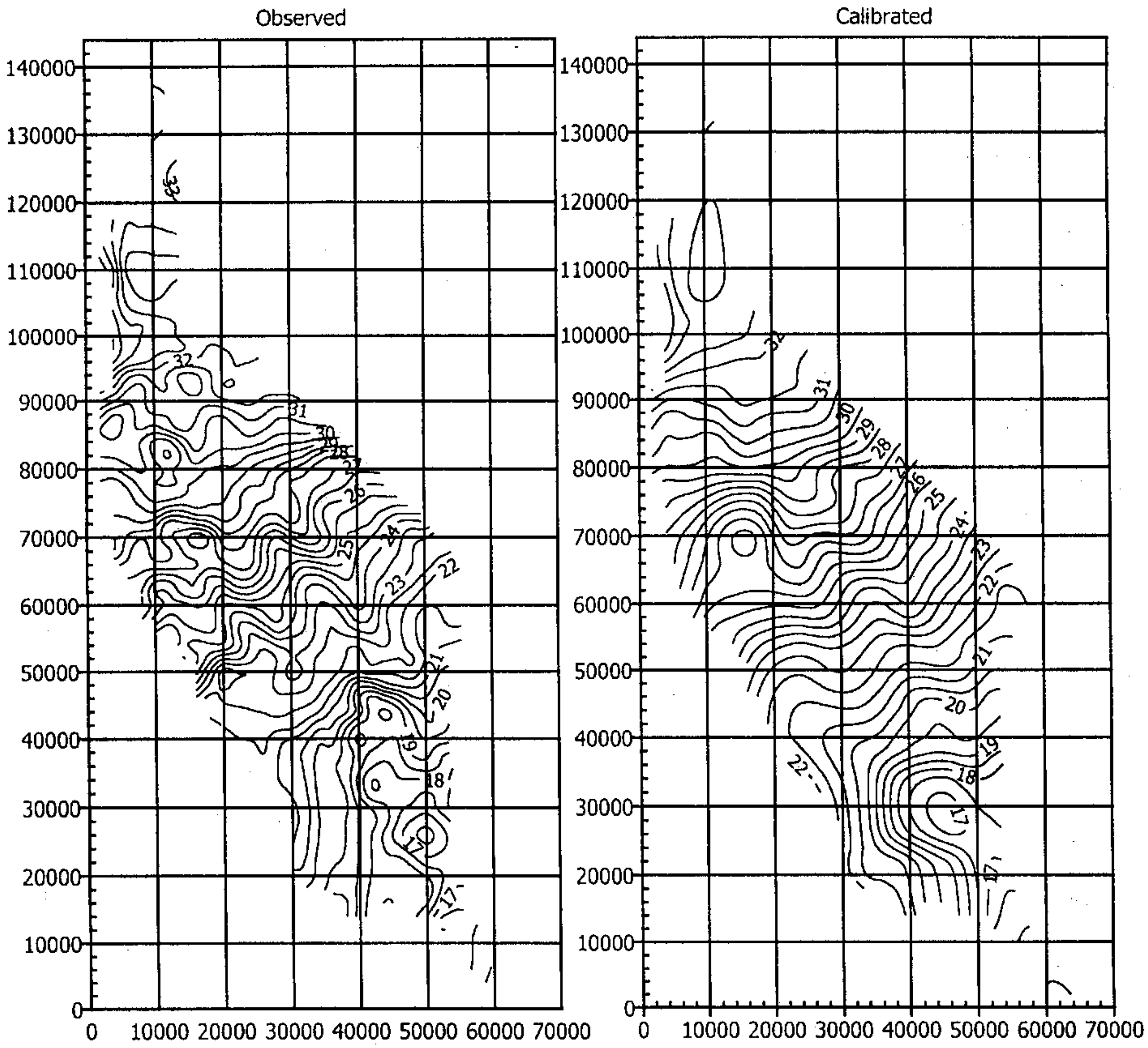
April 1993

Figure II.10. Observed and Calibrated Water Level Contours, April 1993.



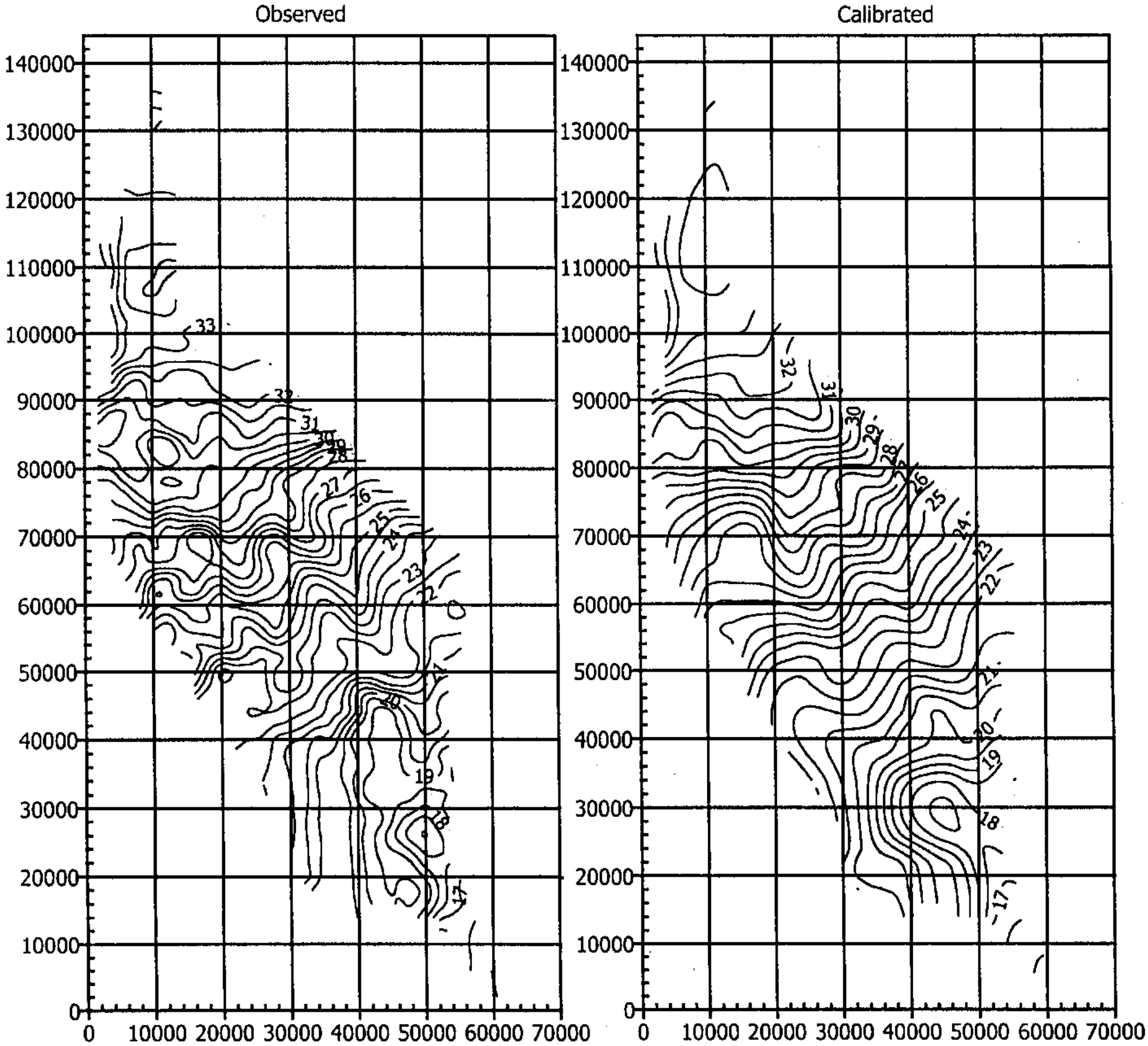
October 1993

Figure II.11. Observed and Calibrated Water Level Contours, October 1993.



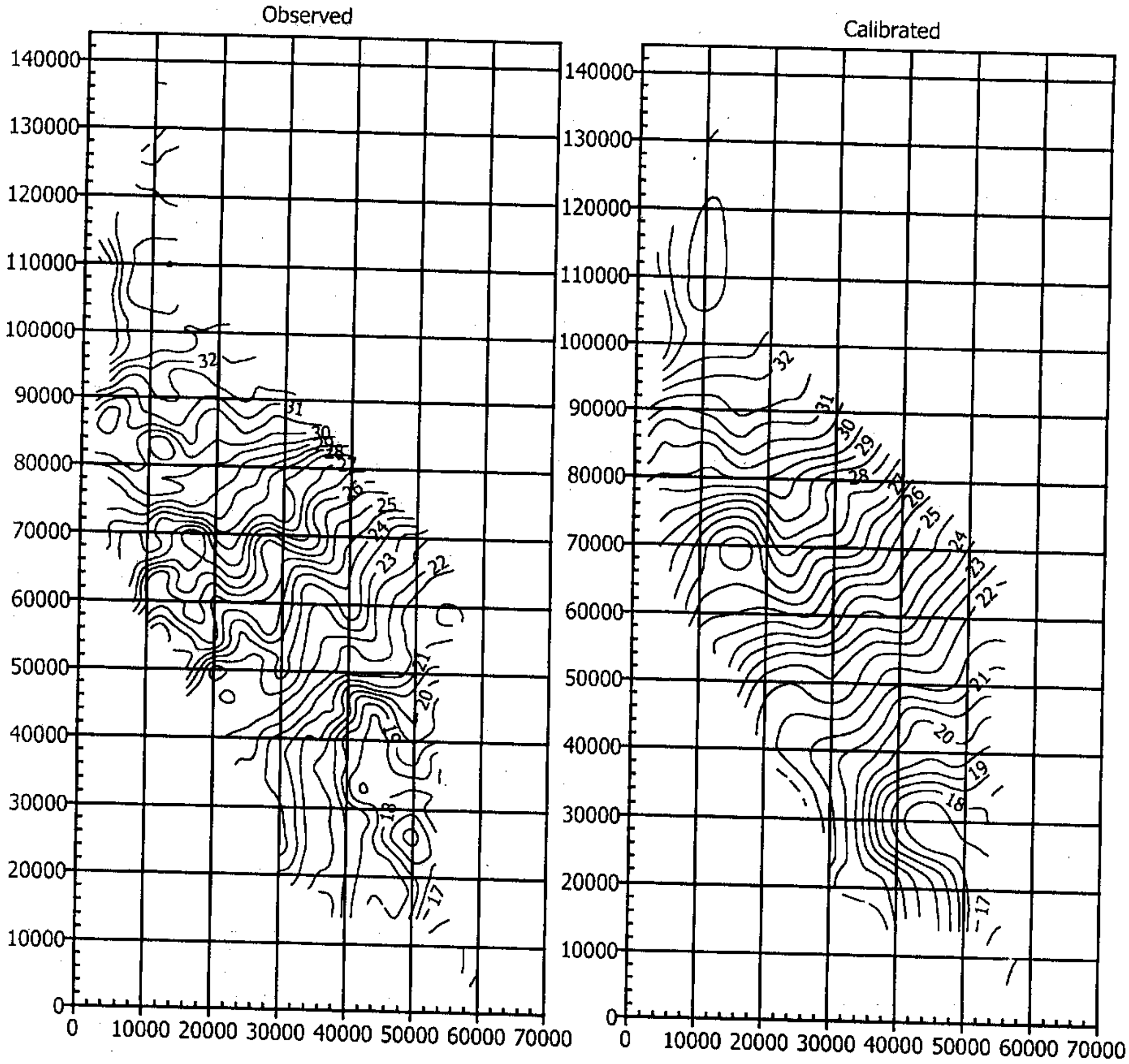
April 1994

Figure II.12. Observed and Calibrated Water Level Contours, April 1994.



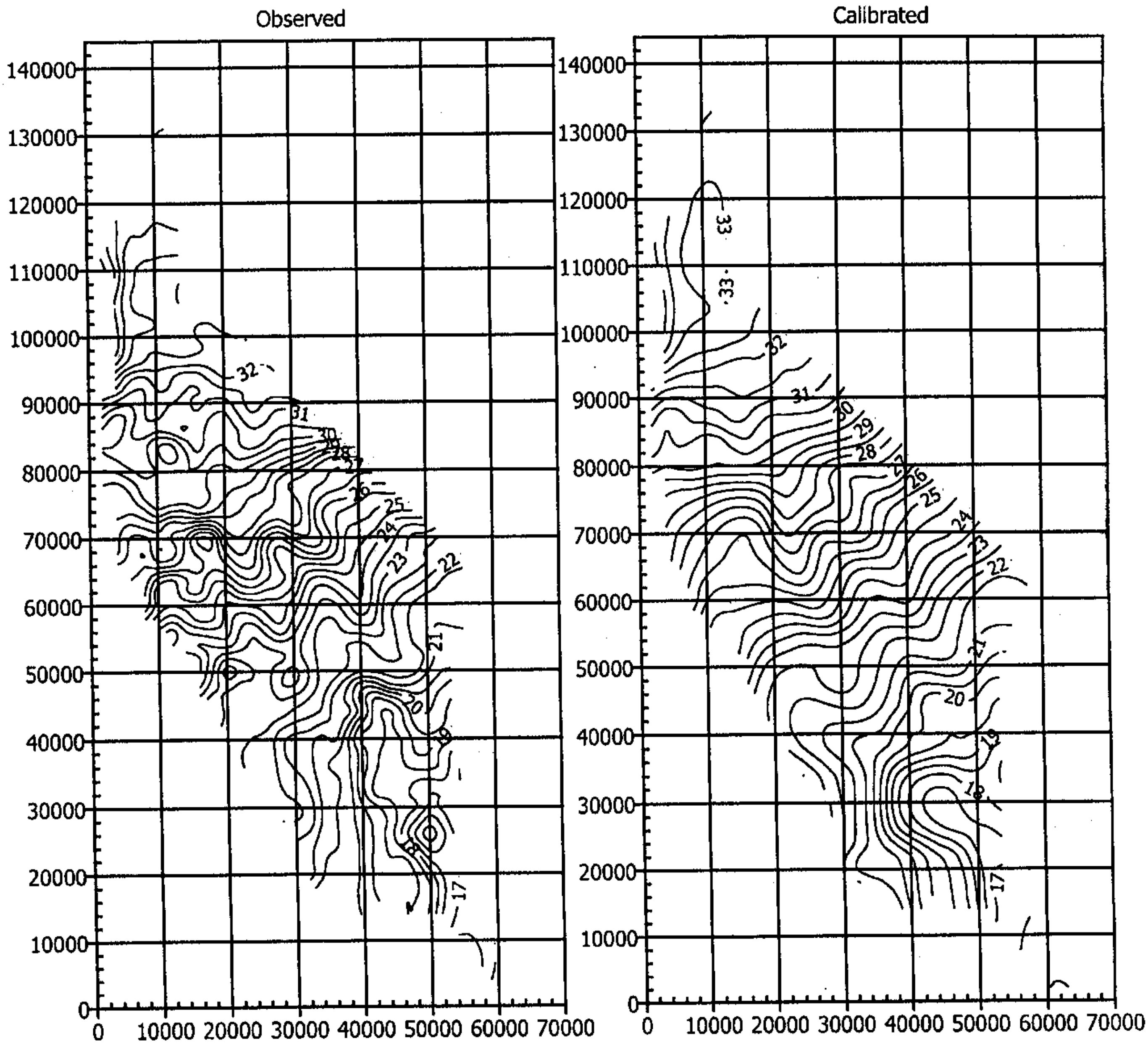
October 1994

Figure II.13. Observed and Calibrated Water Level Contours, October 1994.



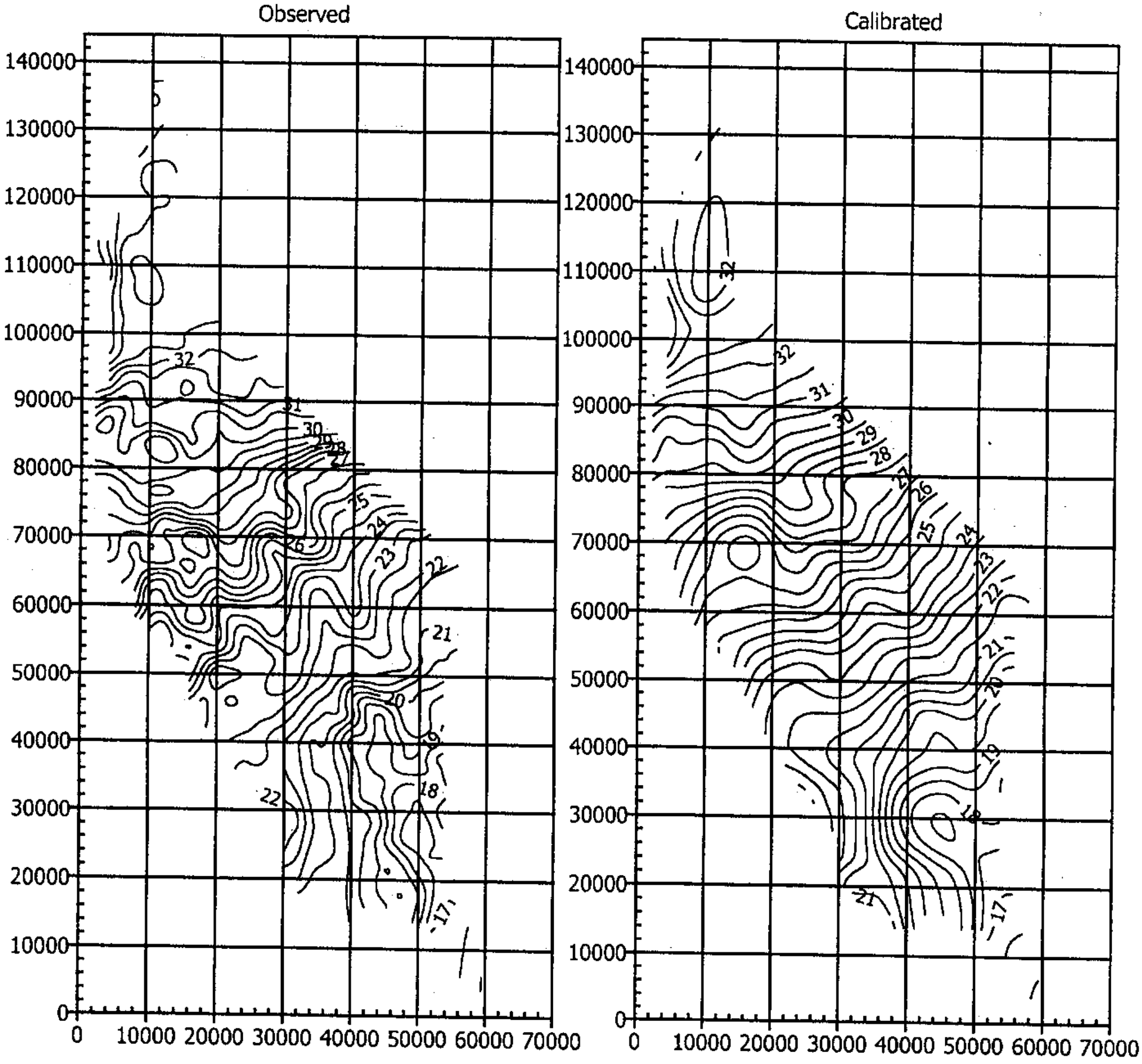
April 1995

Figure II.14. Observed and Calibrated Water Level Contours, April 1995.



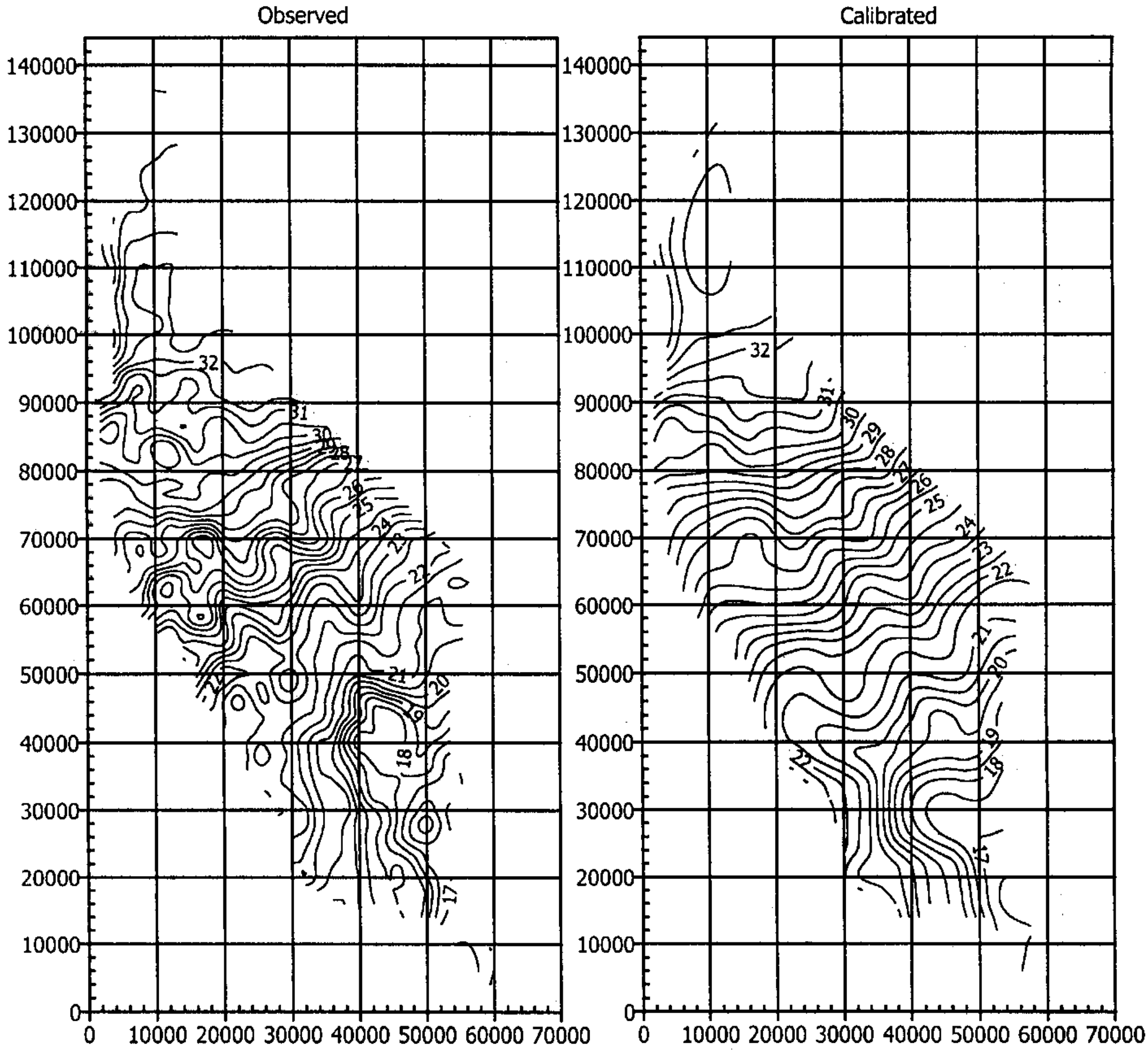
October 1995

Figure II.15. Observed and Calibrated Water Level Contours, October 1995.



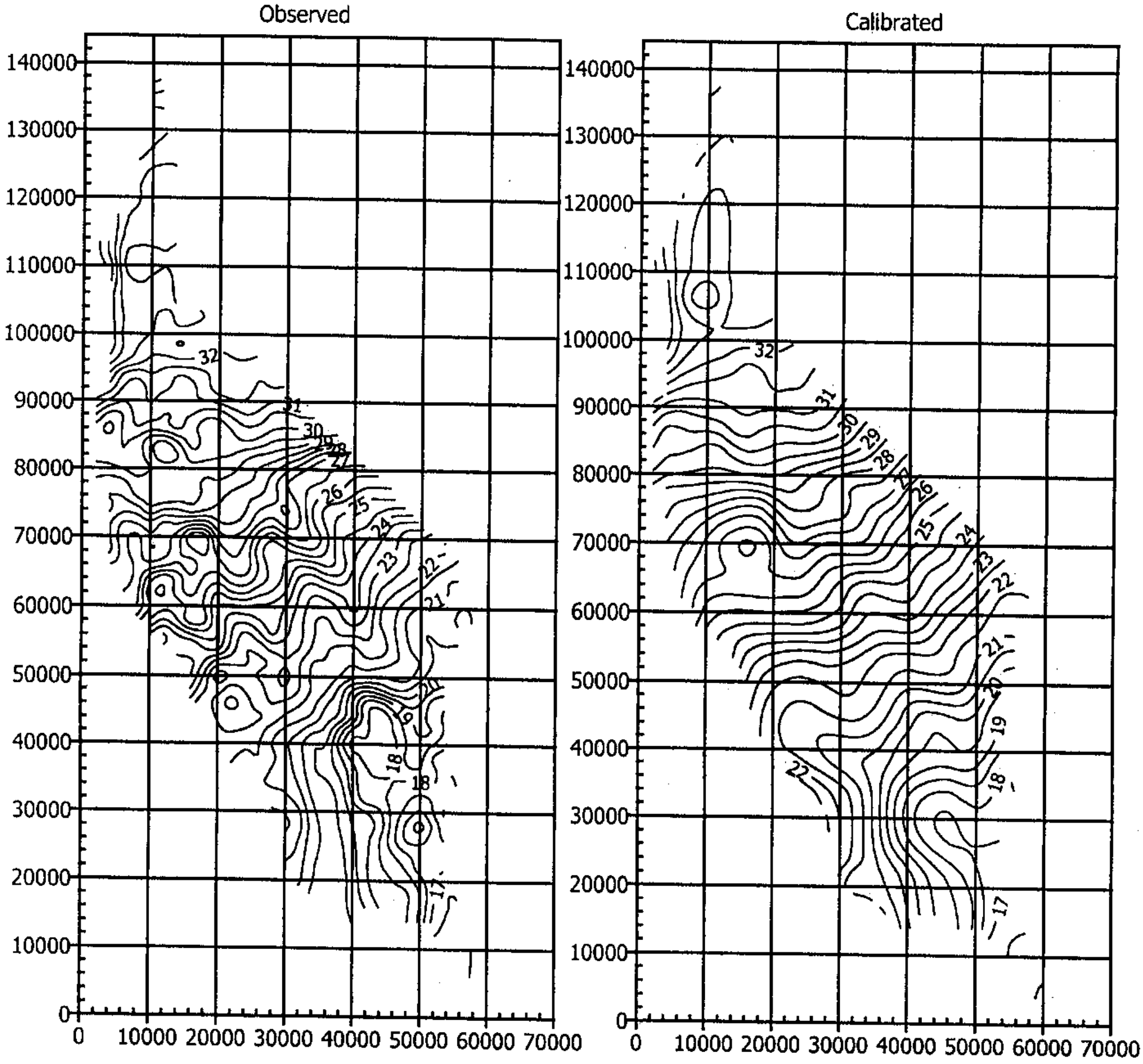
April 1996

Figure II.16. Observed and Calibrated Water Level Contours, April 1996.



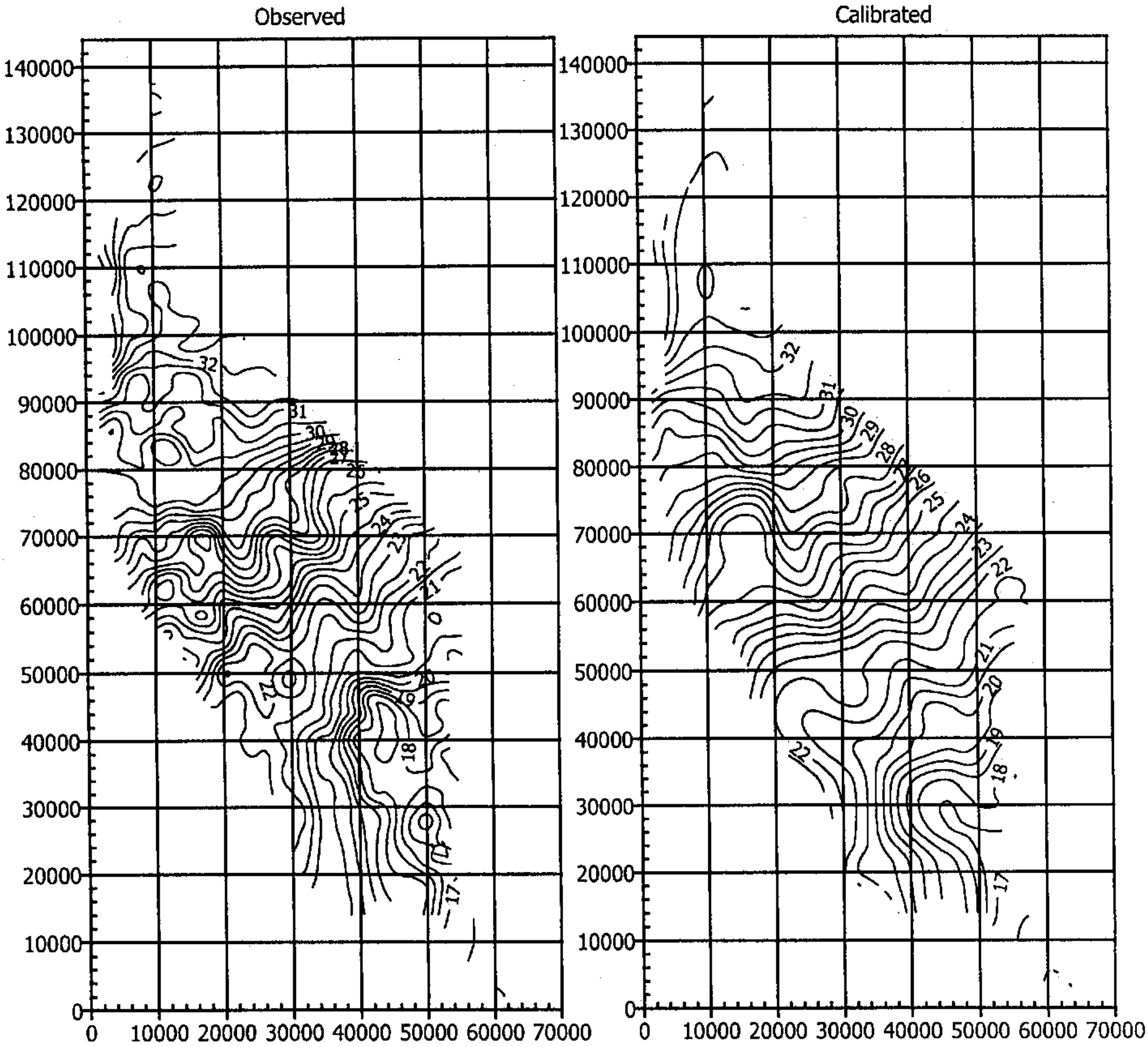
October 1996

Figure II.17. Observed and Calibrated Water Level Contours, October 1996.



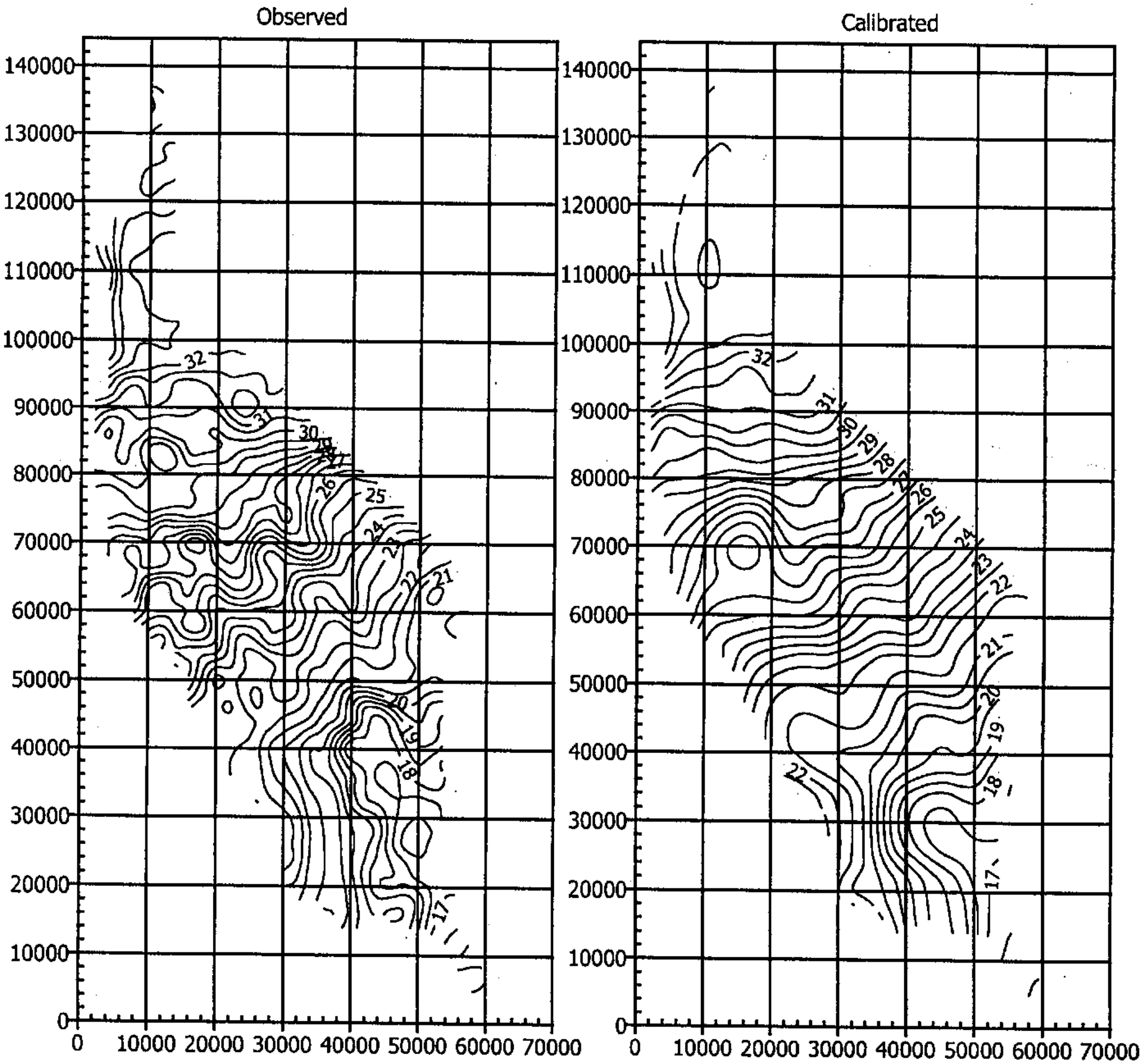
April 1997

Figure II.18. Observed and Calibrated Water Level Contours, April 1997.



October 1997

Figure II.19. Observed and Calibrated Water Level Contours, October 1997.



April 1998

Figure II.20. Observed and Calibrated Water Level Contours, April 1998.

IIMI-PAKISTAN PUBLICATIONS
RESEARCH REPORTS

Report No.	Title	Author	Year
R-1	**Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan** Volume I: Synthesis of Findings and Recommendations	Carlos Garces-R D.J. Bandaragoda Pierre Strosser	June 1994
	Volume II: Research Approach and Interpretation	Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan	June 1994
	Volume III: Data Collection Procedures and Data Sets	Rana M. Afaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R	June 1994
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