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MANAGEMENT OF GROUNDWATER RESOURCES IN PUNJAB, PAKISTAN, USING A GROUNDWATER FLOW MODEL

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A numerical groundwater flow model is used to examine future changes in hydraulic heads for improved groundwater management in Upper Bari Doab, Punjab, Pakistan. A finite difference grid of 45 columns by 27 rows is overlaid on the model area of the Upper Bari Doab, with a constant node spacing of 2 miles in X and Y directions. The boundaries considered were the Ravi and Sutlej rivers and two man-made canals, the BRBD (Bambanwala-Ravi-Bedian-Dipalpur) and the BS (Balloki-Suleimanke) link canals. The boundaries are defined by specified-head nodes with a large value (10E30) of storage factor. Available meteorological, geologic, and hydrogeologic data were used to characterize the groundwater conditions in this aquifer and to simulate potential fields. The model was calibrated with 1966 water levels for steady state conditions and 2004 for transient conditions. The model was then used to simulate the equipotential surface of 2010, which shows an overall fall in groundwater levels up to 35 feet at 1.83 ft/yr in the area. This will eliminate the water logging and salinity problems. Groundwater depletion and pollution may be major problems of the area in the near future.

INTRODUCTION

A two-dimensional numerical groundwater flow-modeling study has been carried out in the Upper Bari Doab to simulate several potential fields under steady-state and transient conditions. The study area is about 1864 mi^2 and extends from longitudes 73°45' E to 74°30' E and latitudes 30°25' N to 31°45' N. The location of the area is shown in Figure 1. Physiographically, the area is part of the Alluvial Plain, which is a dominant unit in the Punjab Plain. It slopes from about 720 ft above mean sea level in the northeast to about 585 ft in the southwest, and has an average gradient of about 1.5 ft/mi. Mainly the River Sutlej, the River Ravi and the abandoned courses of Beas, drain the area. The Upper Bari Doab is the part of Indus Plains in the Punjab region of Pakistan. Prior to 1947 water logging and salinity were not major problems in the Indus Plains, but have become so since 1960 due to development of an irrigation canal network. Changes in the water table over time were due to leaching from the canals and large-scale groundwater withdrawals that were initiated in the late 1960s in order to lower the water table to minimize water logging and provide additional irrigation water. This study was carried out to examine changes in the hydrologic regime caused by past stresses, especially with respect to canal and tubewell development, and to predict the future response of the aquifer system to these stresses.

A finite-difference mesh-centered grid covers the project area with a node spacing of 2 mi in the X and Y directions. The Ravi and the Sutlej were treated as constant head boundaries. Irrigation canals were treated as recharge sources or constant head (Mujtaba, 2002). Hydraulic heads of a number of tubewells and boreholes were used to calibrate the initial steady-state heads produced by the model. Ultimately, the calibrated heads were used to generate the transient conditions of the pumping scenarios and to achieve a controlled water table condition. This information can be used to manage the water logging and salinity problem in the area.

GEOLOGY OF THE AREA

The study area is a part of the Bari Doab with a geological history similar to that of the Rechna and Chaj Doabs. It is covered by alluvium of Quaternary age, which presumably overlies semi-consolidated Tertiary rocks, or metamorphic and igneous Precambrian rocks. The subsurface consists of the following three geologic units in the project area.

Basement Rocks are completely concealed by the overlying Quaternary Alluvial deposits. During the drilling of the special test holes in the north eastern Doab to explore the probable extension of the Dehli-Shahpur buried ridge (a structure on the Precambrian Basement), Precambrian rocks were reported at various places.

Unidentified Units are in the northeastern part of the Doab. Several deep holes penetrated inter-bedded red clays and gravels of fluviatile origin at a depth of about 1,000 ft, which are markedly different from the overlying quaternary alluvial complex. These are termed as “unidentified unit” and may be correlated with the Siwalik system.

Alluvial Complex, which is the principal geological unit, contains the area’s groundwater reserves. Test drilling at different locations has revealed that the upper 600 ft of the alluvium consists of fine to medium sand, silt, and silty clay mixed with concretions of kanker, siltstone and mudstone. The sediments have been deposited by large streams in constantly shifting courses in such a way that the alluvial complex is heterogeneous and individual strata have little lateral or vertical extent. The alluvium is saturated with groundwater to within a few feet of land surface. Replenishment of groundwater occurs by the infiltration of river water, by leakage from irrigation and by the percolation of rainwater (WAPDA, 1980).

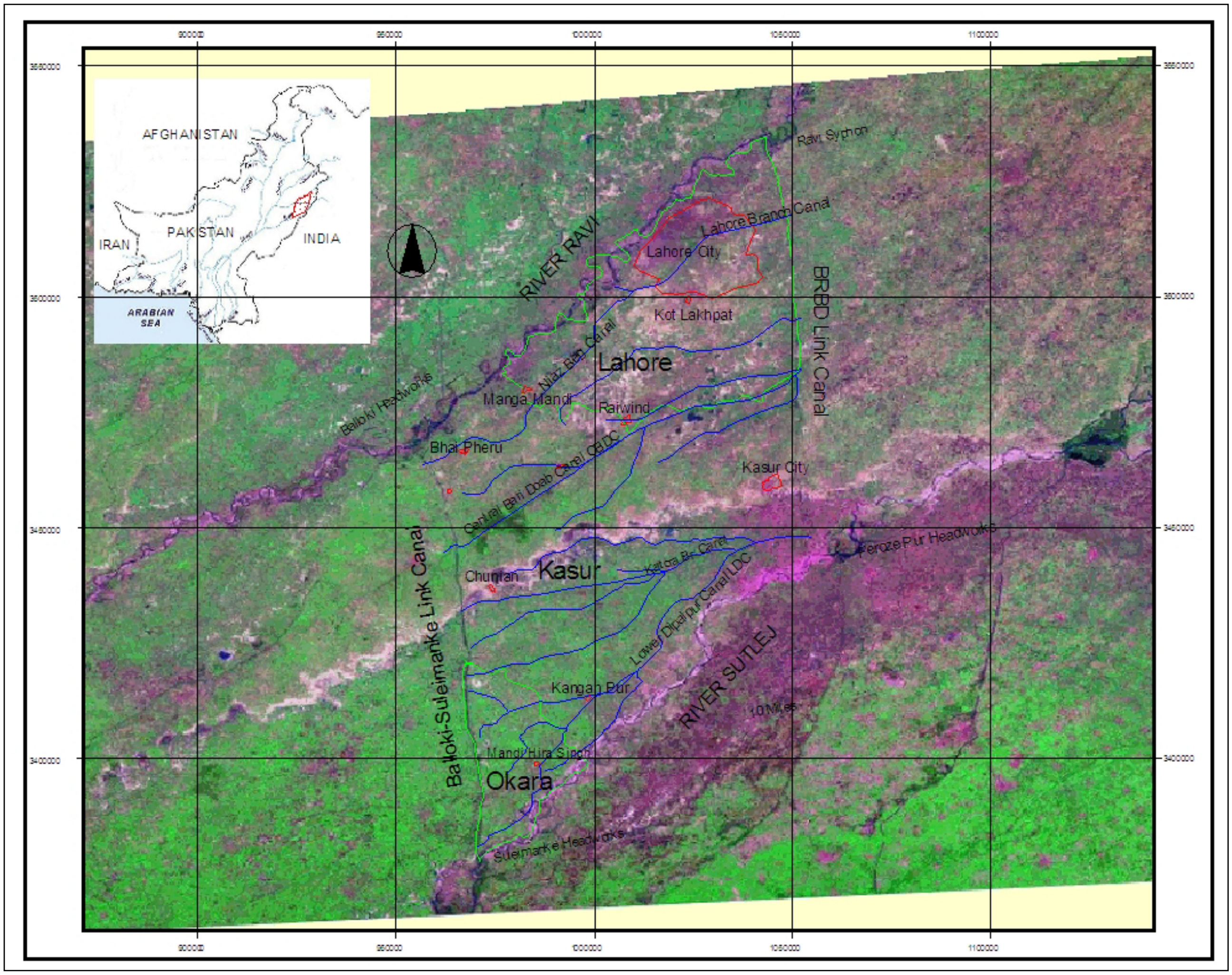

Figure 1. Location of the Upper Bari Doab, Punjab, Pakistan, showing irrigation canal networks, districts, major towns and hydrologic feature.

PHYSIOGRAPHY

The project area forms part of the physiographic unit termed "Alluvial Plain" which is a dominant unit in the Punjab Plain. It can be further divided on the basis of the present relationship of the surface features to the rivers in two sub-heads.

Abandoned Flood Plains, or the cover of the River Sutlej, the former Beas and the River Ravi are 5 to 15 feet higher than their active flood plains and are generally free from normal floods. They have been abandoned in comparatively recent time, which was shown by the presence of oxbow lakes, and by segments of stream channels and natural levees. Being the sites of recharge by rivers in the recent past, these areas are of much hydrologic significance. The abandoned flood plains of the rivers Sutlej and the former Beas is a wide zone of about 30 miles. Photomosaics of the area show that the River Sutlej has oscillated over a band 10 to 30 miles wide in the Doab forming confluences with the Beas at different places; one such confluence is apparent near Chunian. The water table depth varies between 10 to 15 feet and the area is under non-perennial canal irrigation. The abandoned flood plain of the River Ravi is 5 to 6 feet higher than its active flood plain. The river-action in this area is less compared to the abandoned flood plain of the River Sutlej. The water table generally lies between 10 to 15 ft below ground surface and the area is under perennial canal irrigation.

Bar Upland is an interfluvial strip of land, 10 to 20 miles wide, between the Ravi and the old Beas that lies almost parallel to these rivers in the central part of the project area. It is separated from the adjacent flood plains by steep scarps about 30 feet high which decrease in height downstream from Balloki and Chunian.

The bar upland is a uniformly level plain with a few remnants of old channels. The most important channel whose course is very distinct on the photomosaics is the Hudiara Rohi nala, which is in a depression and is 30 miles south of Lahore. It is parallel to the River Ravi from Hudiara village to the Pattoki town and drains a major part of this area into the river. A part of this nala has been converted into a drain that discharges into the river near the village of Miraka (WAPDA, 1967).

CLIMATE

The climate of the project area is semiarid. The summers are hot and last from April to September. The average maximum temperature during this period ranges from about 35°C to over 41°C, and the highest maximum temperature recorded in the project area is 48.3°C. The winters are cool and last from October to March. The average minimum temperature during the period ranges from 4.5°C to 10°C and occasionally night temperature falls below the freezing point. The mean annual precipitation ranges from about 18 inches in the northeastern areas of project to about 8 inches in the southwestern areas; the average for the project area is about 12 inches. The Monsoon starts in the last week of June or the first week of July. It usually results in heavy downpours, which continue with short intervals until September. About two-thirds of the annual precipitation falls during the monsoon season and July is the wettest month. The driest months in the year are October and November. December to March is the season of winter rains; though the total precipitation during this period is meager, it has significant importance from an agricultural point of view (WAPDA, 1967).

TOPOGRAPHY AND DRAINAGE

The Upper Bari Doab is part of a large and continuous alluvial plain formed by meandering streams of the Indus River system. It slopes from about 710 ft above mean sea level in the northeast to about 585 ft in the southwest, and has an average gradient of about 1.5 feet per mile. Parallel to the rivers and in the center of the project area is the high terrace (Dhaya) which rises as much as 30 feet above land surface. Figure 2 shows the topographic contours in the Upper Bari Doab and the high bank in the center of the Doab. Mainly the River Sutlej, the River Ravi and the abandoned course of the Beas drain the area. In addition, remnant channels of the old streams in the area also contribute to draining off the flood waters. Because of the overall gentle relief, the runoff from the area is relatively low (WAPDA, 1967).

EXISTING IRRIGATION FACILITIES

The Central Bari Doab Canal (CBDC) and the Lower Dipalpur Canal (LDC) are the two sources of irrigation supplies for the project area. These canals derive their supplies from the river Chenab through the Bombanwala-Ravi-Bedian-Dipalpur (BRBD) link canal which starts from the Upper Chenab Canal (UCC). The main lines, branches and distributaries of the two systems are shown in Figure 1.

MODEL DEVELOPMENT

The Upper Bari Doab is surrounded by the River Ravi on the north, the River Sutlej on the south, the BRBD link on the east and BS-links on the western side (Figure 2). It covers an area of 1864

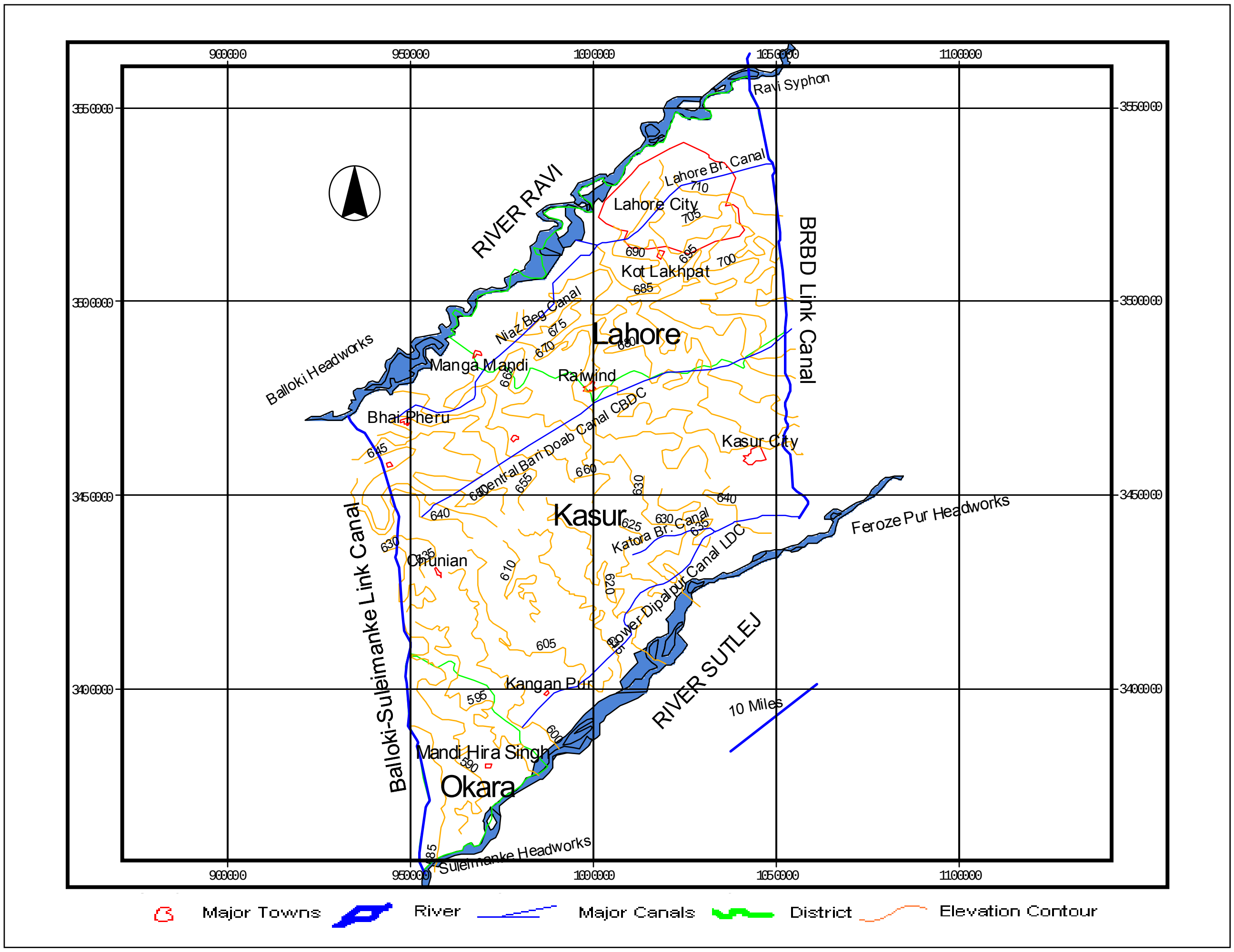

Figure 2. Surface elevation contours, Upper Bari Doab. 5 foot contour interval.

mi^2. Three districts Lahore, Kasur and Okara, partly lie in the Upper Bari Doab. Lahore has an area of 596 mi^2, Kasur an area of 1092 mi^2 and Okara an area of 176 mi^2. A two-dimensional flow model has been developed for the Upper Bari Doab. The Prickett (1971) aquifer simulation model has been selected for the study. The model uses the finite difference method of solving the flow equation. Following are different stages involved in the model development (Anderson and Woessner, 1992).

Boundary Conditions

The rivers Ravi and the Sutlej on two sides of the Upper Bari Doab form the physical boundaries, while on the other two sides, link canals are hydraulic boundaries (Irrigation and Power Department Lahore, 1978; Irrigation Drainage and Flood Management, 1970; W.R.M, 1994; W.R.M, 1996). The two hydraulic boundaries, i.e. BRBD canal and BS link canal, were defined on the basis of a water table map of the Upper Bari Doab. The heads at all nodes along the boundaries were fixed at a constant value. Very high values of storativity (IE30) were assigned to these nodes in order to treat them as constant head. The nodes outside the area and no-flow boundary nodes in the project area were assigned a very low value of hydraulic conductivity (i.e. 1E-9).

Model Layers and Grid Layout

The Upper Bari Doab aquifer is considered one hydrologic unit of 250 ft thickness (Mujtaba, 2002). It is approximately a horizontal stratum of uniform thickness. A mesh-centered finite difference grid was overlaid on the domain so that X and Y were colinear with K_x and K_y. The grid was equally and regularly spaced with 2 mi in both the X and Y directions. As such, a rectangular grid with 45 columns by 27 rows was used, which produced 1215 total nodes (Figure 3).

Model Hydraulic Conductivity (K)

Twenty eight wells had laboratory hydraulic conductivity values ($K_{lab)}$. Of these, five wells also had field hydraulic conductivity ($K_{pump)}$ (Bennett et al., 1964; WAPDA, 1980). It was assumed that the area around a well has the same field hydraulic conductivity as the well. The difference between K_{lab} and K_{pump} was calculated for each of the five wells and termed K_{diff}. Each K_{diff} was assigned to a zone surrounding it by the Thyssen Polygon method (Fetter, 2001) and added to the K_{lab} value of each well lying within that zone to produce a K_{model} for each well. These twenty eight K_{model} values were grouped into nine zones by cluster analysis (SPSS, 1998) and each zone was assigned a single value of K_{model}. It was assumed that $K_x = K_y = K_{model}$ and these were input in the model (Figure 3).

Model Specific Yield (S_y)

The specific yield (S_y) values were available from field measurements for five wells (Bennett et al., 1964). The field values of S_y were grouped in the same way adopted for K_{pump} zones. These 'S_y' values were used as input in the transient simulations (Figure 4).

Model Recharge Estimation

a. Groundwater recharge by watercourse, fields and distributaries is taken to be 20% of the total deliveries (Ahmad and Sergio, 2001).

b. Eighty-eight percent of the total seepage from the link canal was assumed as groundwater recharge (WAPDA, 1980). The seepage was assumed as 10% of total link canal delivery.

c. Recharge of rainfall to the groundwater system was taken as 10% of the total annual rainfall (Akhtar and Ahmad, 2001).

d. Approximately nineteen percent of the total tubewell abstraction was considered to recharge the groundwater (Ahmad and Sergio, 2001). It is also called recirculation of groundwater.

Model Discharge Estimation

Tubewells are the main source of groundwater abstraction (Planning Unit, 1975; Bureau of Statistics, 2000). As about 19% of the total tubewell abstraction will again recharge the aquifer, the remaining volume of water is considered as discharge (WAPDA, 1967; WAPDA, 1980; NESPAK and SGI, 1991).

Based on canal deliveries, tubewell irrigation and agricultural importance, the Upper Bari Doab was divided into nine zones (WAPDA, 1967). The recharge and discharge were estimated for each zone and input to the model in the transient simulation (Figure 4).

THE MODEL

The Prickett-Lonnquist Aquifer Simulation Model (Prickett, 1971; Prickett et al., 1981) modified by Thraikill (1988), and Akhta and Ahmad (2001) was used in the present study. It simulates two-dimensional groundwater flow in areal and profile orientations. It is block-centered but can accommodate mesh-centered flux boundary conditions with consistent and inconsistent units.

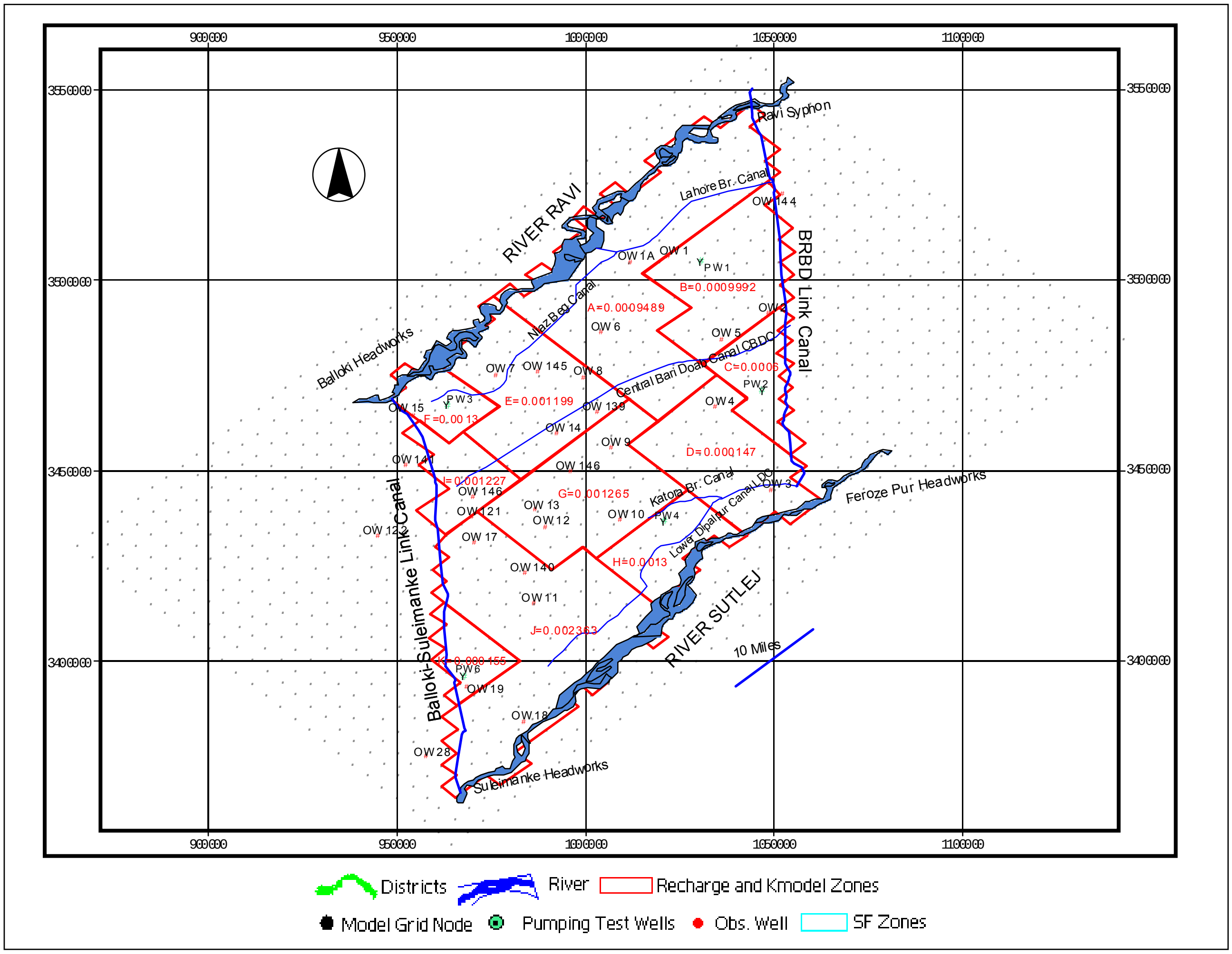

Figure 3. Model grid, K-pump zones, pumping test and observation wells, Upper Bari Doab.

STEADY-STATE SIMULATIONS AND CALIBRATION

The data file was prepared with the initial estimated parameters and the model was run for steady-state conditions for 20 years with two time steps each of 10 years. The tolerance error was set to be 0.1 feet. The model converged to a solution but the heads in the several zones were deviating from the observed heads of 1966 and artificial sources and sinks were developed in different zones of model grid. The K-values were adjusted gradually by the trial-and-error procedure until both groundwater mounds (sources) and depressions (sinks) were diminished. Discrepancies in the calibration were removed by minor adjustments in the areal recharge of these areas. The steady-state calibrated with 1966 observed heads was achieved with mean error ME = 1.12 ft, mean absolute error MAE = 3.45 ft and root mean square error RMS = 3.75 ft. an equipotential map and match of observed and model heads after calibration are shown in Figure 5 and Figure 6 respectively.

After model calibration, the steady-state model was tested for convergence i.e. whether the model calibration is reliable or not. For this purpose 5 feet was added and then subtracted from all non-constant heads in order to perturb them, and the program was then rerun. The difference in final heads between these runs is a measure of the lack of convergence. The difference ranged from – 0.0013 to 0.0002 when 5 ft was subtracted from all non-constant heads, and ranged from - 0.0012 to 0.0003 when a constant value was added, which suggest a good convergence criterion.

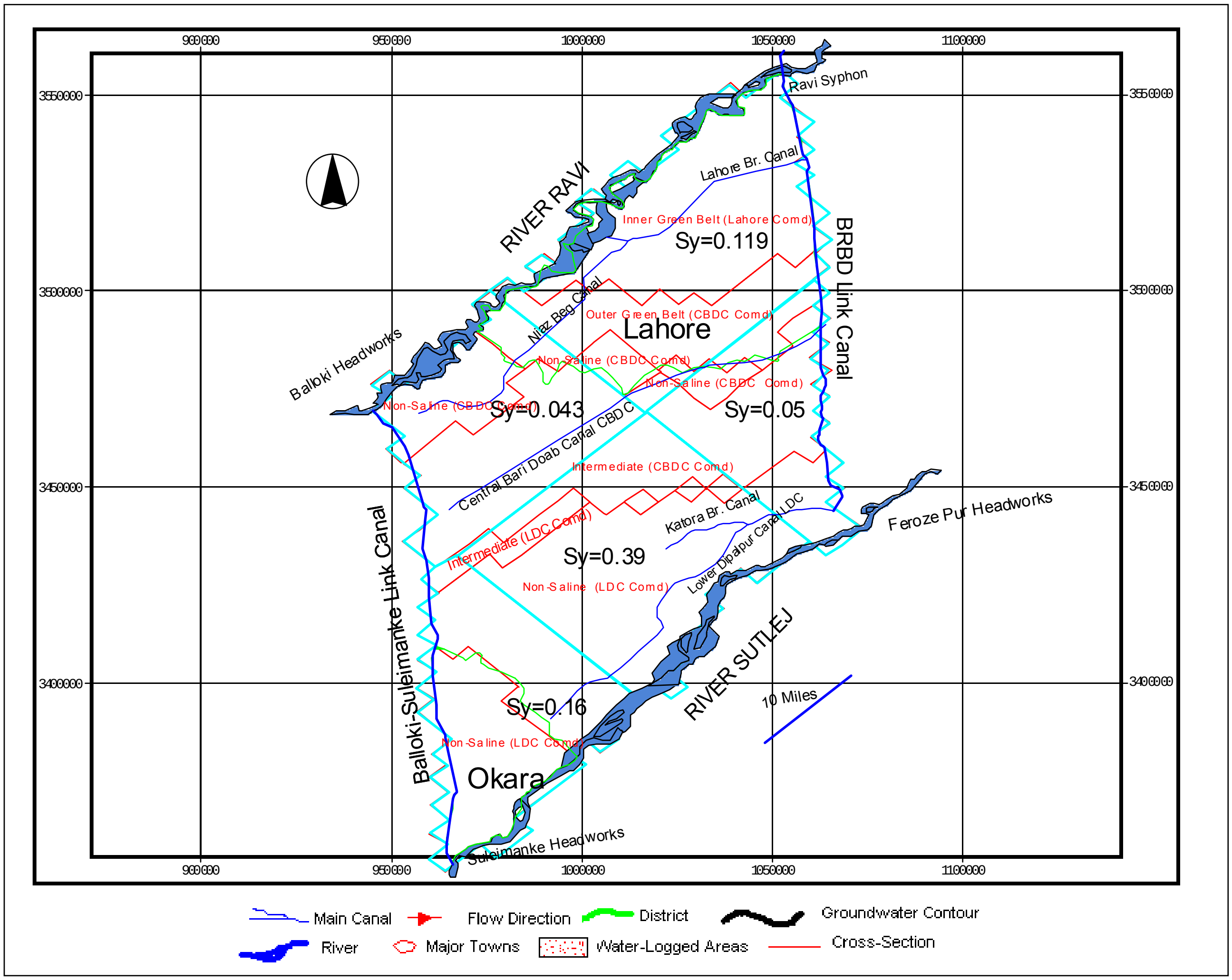

Figure 4. Model recharge, discharge and specific storage zones of Upper Bari Doab, transient simulation.

Sensitivity analysis was performed for hydraulic conductivity (K) and recharge after the steady state calibration. Optimum values (K_{opt}) were multiplied by factors ranging from 0.2 to 2 and simulations were obtained for each factor. The criteria of study were the mean and standard deviation (SD) of the difference between model and observed heads at the test wells. Results showed that the mean was more sensitive to the value of K_{opt} than SD at lower values of K. Similarly recharge values of four branch canals, including a few that were not used during calibration adjustments, were multiplied by a factor ranging from 0.2 to 2 and simulations were performed for each. The mean difference was quite sensitive to changes in recharge and the standard deviation was somewhat less so (Mujtaba, 2002).

TRANSIENT SIMULATIONS AND CALIBRATION

Input data was prepared for transient simulations using all available hydraulic, meteorological, flow, and recharge/discharge data. The data for every year from 1966 to 2006 was not available, so the whole period was divided into loops and the model was run to simulate transient conditions in loops as 1966-79, 1979-89, 1989-95, 1995-2000, 2000-04, 2004-06 and 2006-2010 for predictions. Storage Factor, a product of specific storage, X and Y model grid spacing was input for each zone in transient simulations. The model was run for all above loops in transient conditions where the heads from the previous run were used as input for the next simulation. Up to 1989 the

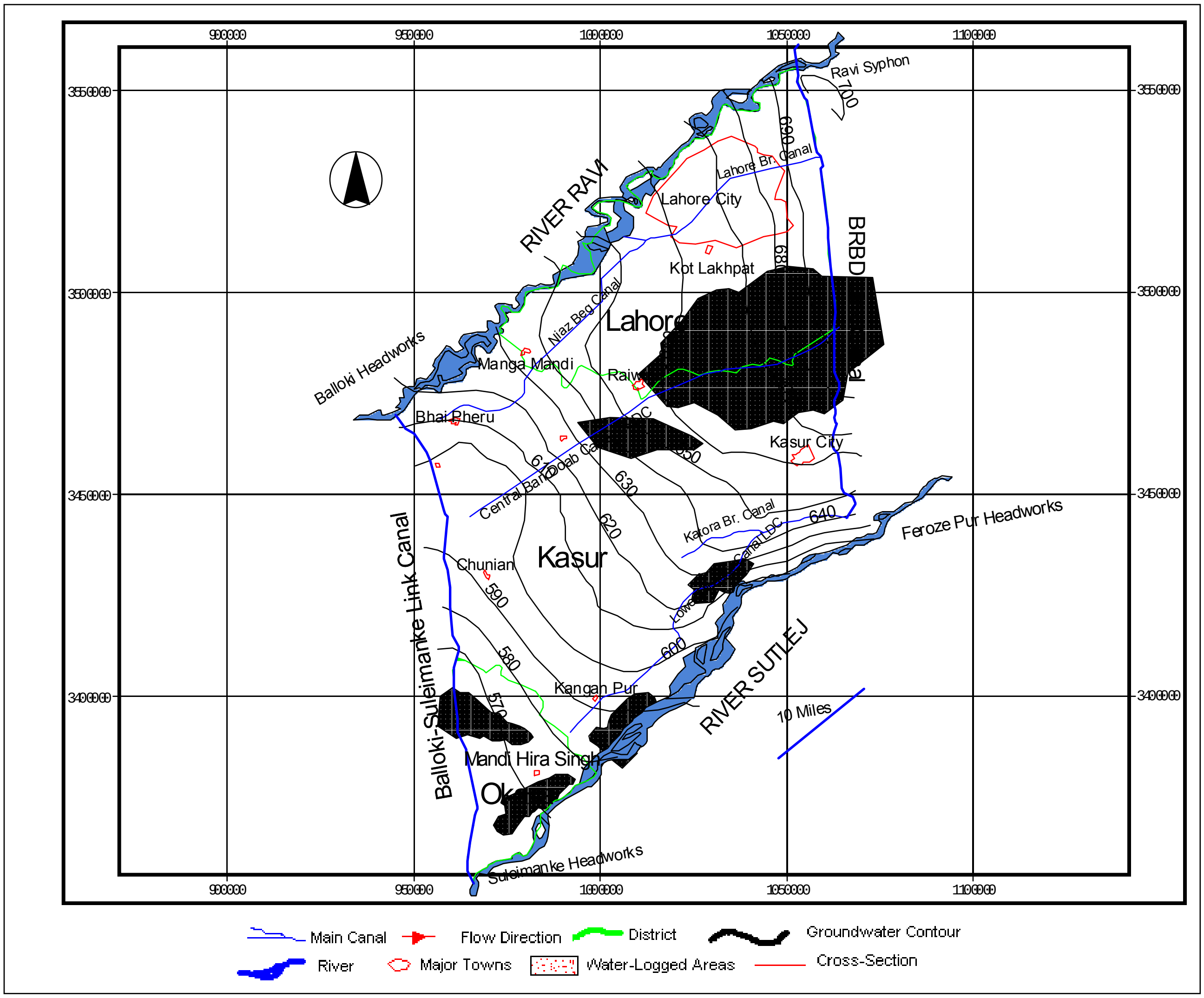

Figure 5. Equipotential map for Upper Bari Doab for 1966 after steady state calibration. Contour interval 10 ft. Water logged areas also shown.

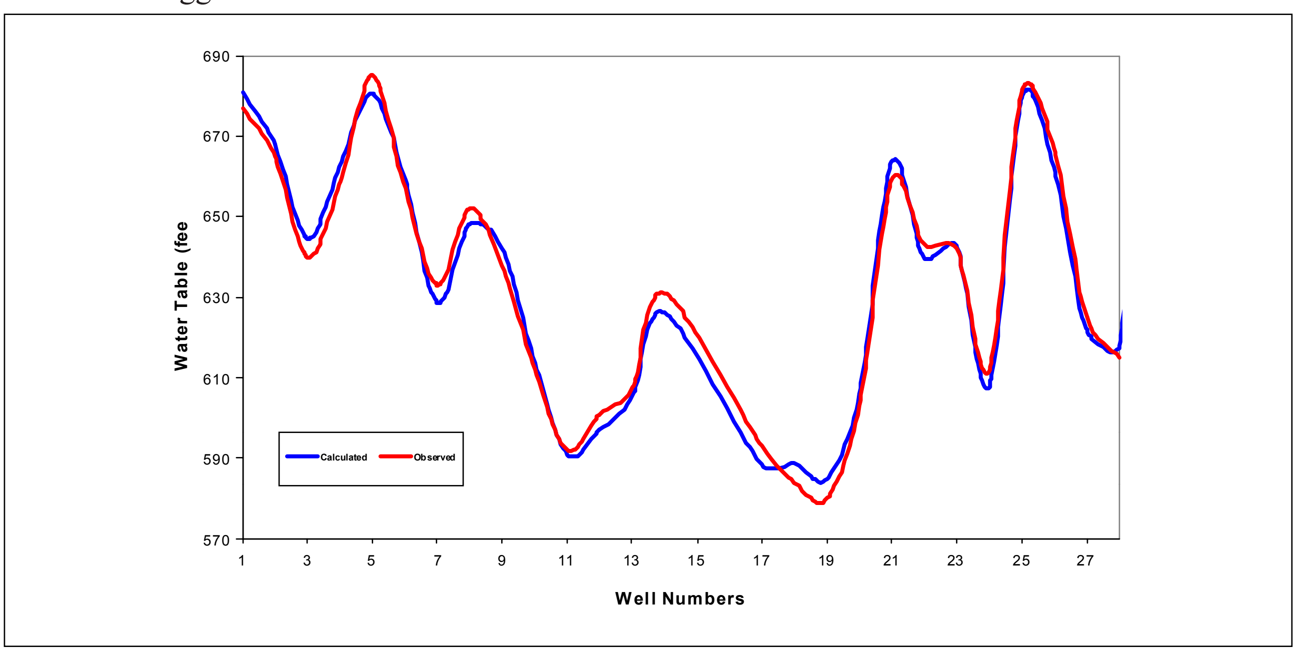

Figure 6. Comparison of observed and model calculated groundwater heads.

water table showed a rise of 0.5 to 1 feet in areas adjoining the major branch canals, but were similar in the flow regimes as in steady-state. From 1989 to 1995, water table decline was observed in some areas but that decline was not so significant.

From 1995 water levels started declining all through Upper Bari Doab in general, and especially in parts of Lahore City, Bhai Pheru, and Mandi Hira Singh. These groundwater depressions were extended in later years, and in 2004 two prominent sinks emerged near Bhai Pheru and Mandi Hira Singh. In Lahore City a general decline of water table was observed. For 2004 the model was calibrated again with transient conditions. The model produced a very much similar condition as the observed water table of 2004 (Land Reclamation Directorate Punjab, 2006). The differences in observed and calculated water levels were adjusted by finely tuning the specific storage. The model was run for 2004-2006 after transient calibration for post auditing the model predictions. Model results almost matched the water table condition presently existing in the area (Scrap Monitoring Organization, 2006). The decline of the water table is going on, and the cones of depression in the area are expanding and deepening. Finally, the model was run for four years to predict the water levels for 2010. An average water table decline was 30 to 35 feet in Upper Bari Doab was seen compared to 1966. A groundwater depression in Lahore City and the cones in Bhai Pheru and Mandi Hira Sigh expanded and further deepened.

RESULTS AND DISCUSSION

Steady state simulation results of 1966 indicated that about 135 mi^2 of Upper Bari Doab was affected by twin problems of waterlogging and salinity along River Sutlej, links and main canals (Figure 5). The waterlogged areas eventually turned into salinized zones due to a repeated process of evapotranspiration over the rising water table. Results of the transient simulations have established a rising trend of the water table up to 1989 in some parts due to the irrigation network, and it remained at the same level in most parts as in 1966. After 1990, the rapid development of tubewells for increasing requirements of irrigation water, and reduction in canal deliveries caused the water table to decline in the study area. Apparently, there are no threats of waterlogging in most areas of the Upper Bari Doab, except adjacent to the confluence of BRBD and CBDC where this problem persisted beyond 2006.

From the steady-state equipotential surface map, it was inferred that the BRBD link canal was a losing stream, while the BS-link canal was a gaining stream. Both the Ravi and the Sutlej rivers were gaining (Figure 5). But after transient simulation the nature of all canals and rivers changed significantly. BRBD would keep its losing character up to 2010 but the three others would change their characters partially. The Ravi would be gaining in the eastern parts and changed to losing in the western parts of the study area, and it would contribute to the groundwater near Bhai Pheru. The Sutlej would also be losing in west and would contribute to groundwater. BS link canal would be losing except near its confluence with CBDC where it would be a gaining stream (Figure 8). A decline of 5 to 25 feet was observed in the groundwater mound since 1990 along CBDC from east to west. It would separate two cones of depression in its western parts to merge into a bigger cone causing rapid groundwater depletion (Figure 8).

Equipotential maps and cross-sections from transient modeling scenarios are indicating a gradual decline of the water table, development of sinks, and minor rises along branch canals in Upper Bari Doab (Figures 7 and 8). Average water table depth up to 2010 in Lahore would be 35 ft at the rate of 1.87 ft/yr since 1990. Groundwater mining is more extensive in the center of Lahore

City than in the northeastern parts of city and it could be up to 45 ft near the center of the city in 2010. The equipotential map for 2010 shows the possibility of two cones of depression in Lahore beyond 2010, one in the northeast of city and the other in the southwest. Kasur had an average depletion of 24 ft at the rate of 1.23 ft/yr until 2004 and it would increase to 34 ft with 1.71 ft/yr until 2010. The maximum estimated fall from modeling results would be 42 feet with an areal extension of about 20 mi^2 in the vicinity of Bhai Pheru until 2010. Groundwater levels are less influenced south of Kasur city due to the confluence of the LDC and BRBD. Okara water table depletion would be 38 ft with a decline rate of 1.93 ft/yr and maximum model estimated drop would be 42 ft with an areal extension of about 40 mi^2 in the vicinity of Mandi Hira Singh in 2010 (Figures 8 and 10). The modeling study predicted that the water table will drop further until 2010 at an average rate of 1.83 ft/yr in some areas of Kasur, Okara and in Lahore City (Figures 9 and 10). The maximum fall of the water table of about 35 to 45 feet has been predicted from the modeling results, to occur in Okara, Kasur and Lahore.

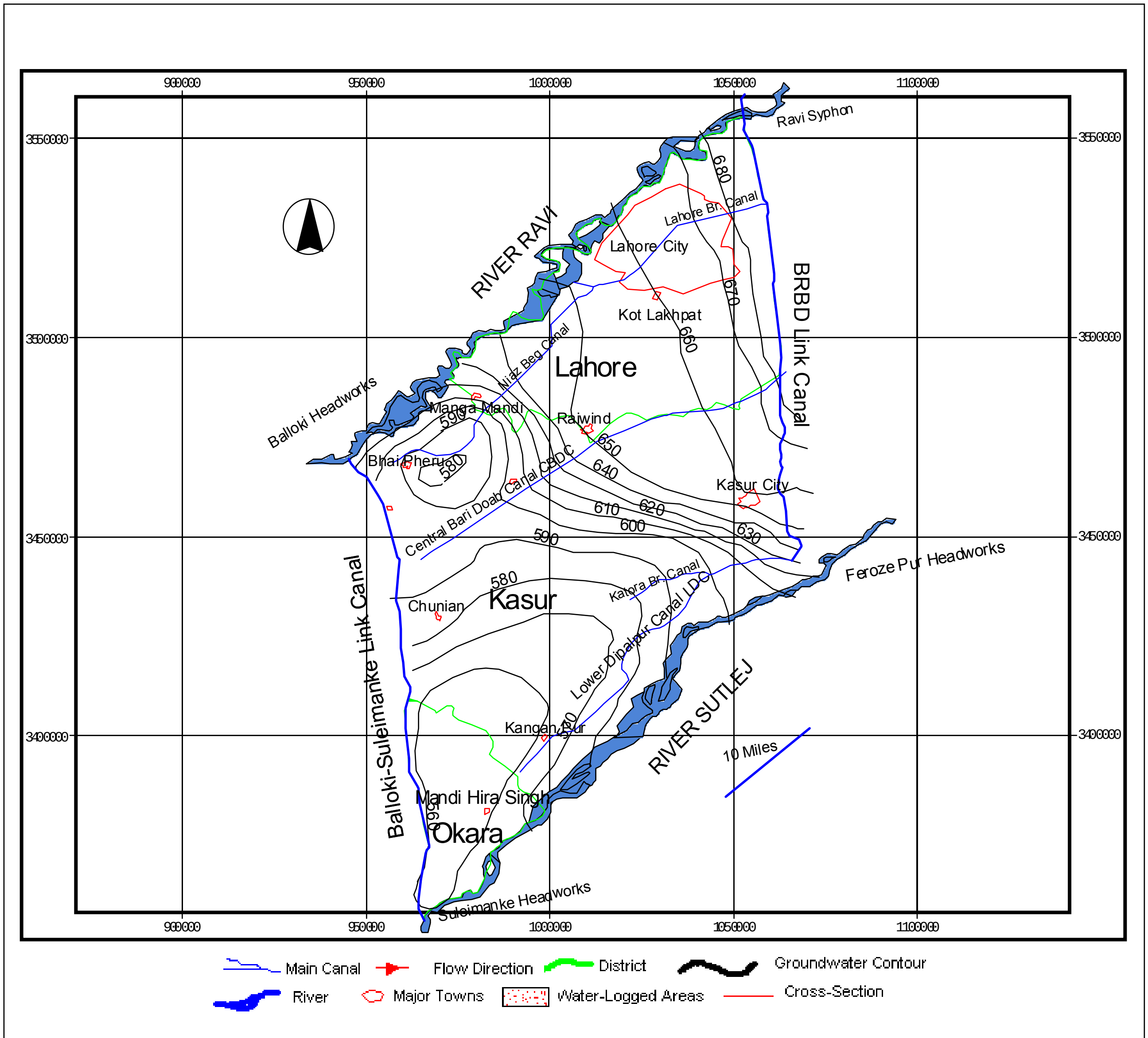

Figure 7. Equipotential map of Upper Bari Doab showing groundwater elevations for year 2006. Contour interval 10 ft.

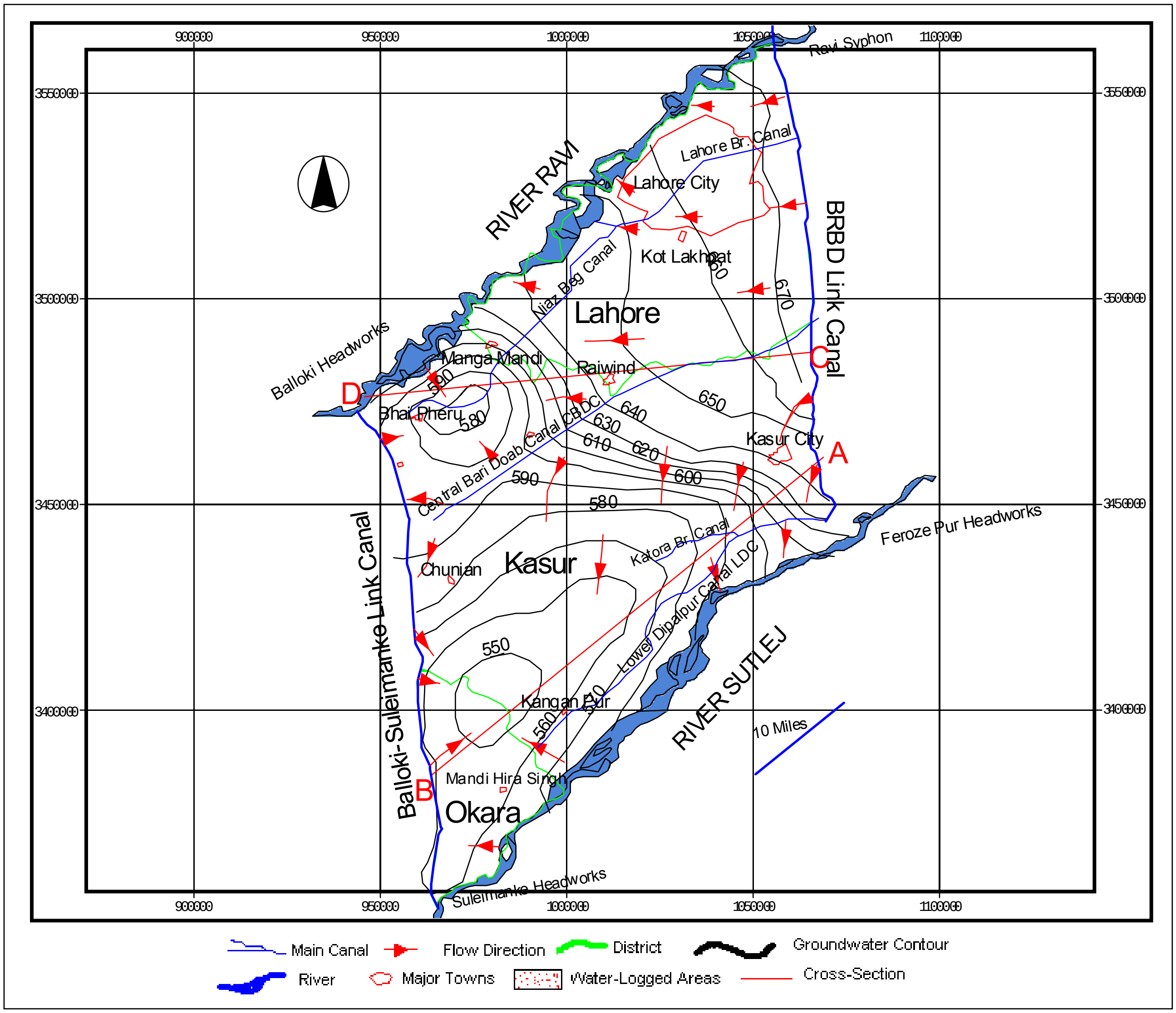

Figure 8. Equipotential map of Upper Bari Doab showing groundwater elevation for year 2010 after model predictive simulation. Contour interval 10 ft. Cross sections and flow direction also shown.

CONCLUSIONS

1. Results indicate that groundwater resources are being depleted gradually, due to extensive tubewell development for irrigation water since 1990 and reduction in the canal deliveries due to drought conditions, prevailing for the last 6 to 10 years, which reduced the groundwater-recharge component, canal deliveries and ultimately, canal seepage and canal recharge to groundwater.

2. Areas of rapid declining levels are northwestern parts of Kasur and the southwestern side of Upper Bari Doab that includes parts of Okara and Lahore City in general.

3. The model predicted rates of water table decline are 1.87, 1.71, and 1.93 ft/year for Lahore, Kasur and Okara, respectively.

4. The trend and general direction of groundwater flow changed as it was in 1966 due to inflow-outflow components variations, changes in the hydraulic gradient, and recharge.

5. Groundwater recharged by rivers would cause groundwater pollution due to polluted surface water bodies receiving city and industrial toxic drainage.

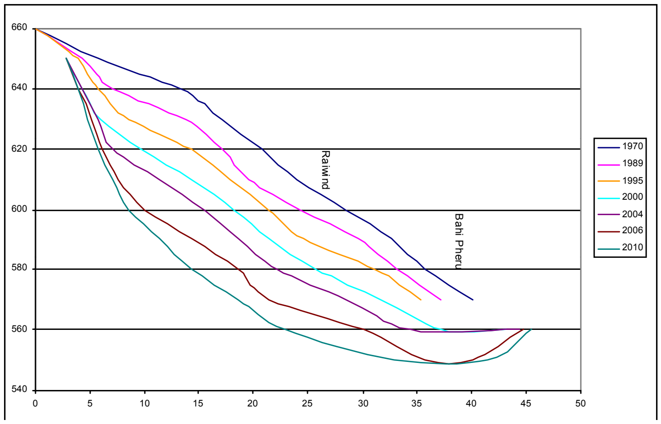

Figure 10. Water table elevation for different years along AB

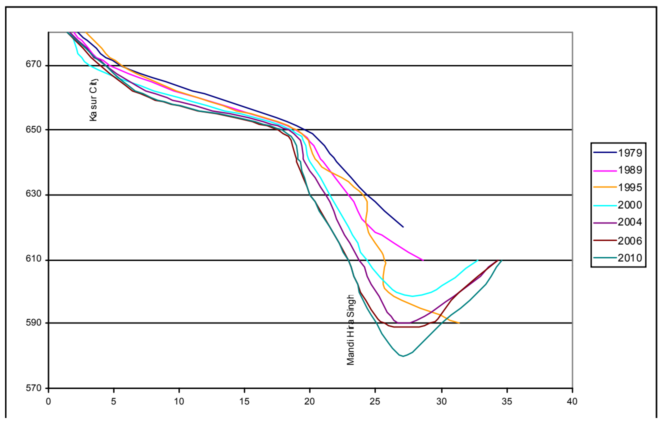

Figure 10. Water table elevation for different years along CD.

6. Instead of waterlogging and salinity, problems of water shortage and groundwater pollution will likely evolve in the future.

7. Due to large groundwater withdrawal and heavy construction, the possibility of surface subsidence is also present in the Upper Dari Doab and especially in Lahore.

RECOMMENDATIONS

1. A close monitoring of private tubewells development should be made in areas where the water table has started to show trends of consistent decline.

2. There should be proper planning so that the groundwater resources are properly managed but not allowed to deteriorate.

3. A hydraulic budget of the Upper Bari Doab should be developed on an annual basis to manage and control the groundwater development.

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