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Research Article

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Building MODFLOW Model in ModelMuse GUI For Bari Doab

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Abstract

This steady state groundwater model was developed in ModelMuse GUI developed by USGS, for irrigated areas of Bari Doab with an area of 2.95657 Mha (million hectares) GCA (gross command area). Under this study, the data of depth to watertable in all canal commands of Bari Doab was also collected and analyzed. Canal water supplies have recharged the aquifer and created a groundwater resource in the command areas. Continued abstraction and extensive exploitation of groundwater have resulted in the depletion of the ground watertable especially in fresh groundwater areas. Although there is clear evidence of groundwater over exploitation, in the form of falling watertables, even then, hundreds of new wells are being installed every year without knowing the sustainability of the aquifer for meeting this increased demand.

For this purpose, ModelMuse GUI (graphical user interface), which is downloadable without any fee, was used for building MODFLOW model for Bari Doab, which can be used for different scenario simulations such as climate change and re-allocation. Model was calibrated and graphs were prepared in Excel. According to the calibration results, farmers are pumping 50 to 60 % higher than canal and rainfall recharge to groundwater.

1. Introduction

1.1 Groundwater in Bari Doab

The alluvial sediments that comprise of the aquifer exhibit considerable heterogeneity both laterally and vertically. Despite this, it is broadly viewed that the aquifer behaves as a single contiguous, unconfined aquifer. The study of the lithologic logs of boreholes (180 to 300 m depth) and test wells (30 to 110 m depth) indicates that Bari Doab consists of unconsolidated sand, silt and silty clay, with variable amounts of cankers. The sands are principally grey or greyish-brown, fine to medium grained and sub-angular to sub-rounded. Very fine sand is common for most of the bores: finer grained deposits generally include sandy silt, silt and silty clay with appreciable amounts of canker and other concretionary material. Re- evaluation of the original dataand geological sections (Unites States Department of the Interior, 1967) suggests that in the area between Lahore and Okara, there is a moderately persistent and alternate layer of finer materials (clay, silt) of about 15-30 m thickness without any regularity or continuity, and that these finer materials are more prevalent towards the Balloki side i.e. head of the irrigation systems [1]. The near surface layer of clay/silt, 6-15m thick, is also prominently evident. However, thick layers (40 m of very fine to medium sand) were also found at deeper depths of the Bari Doab aquifer. Within the Middle Zone, as represented by the cross section near Sahiwal, silt/clay layers tend to be thinner and distributed unevenly, both vertically and horizontally. More importantly, the section shows that the aquifer characteristics tend to be very much sandy towards Harrapa town. Also, detailed study of lithologic logs of boreholes of BARI DOAB have shown sandy aquifer without any marked clay lenses. The Lower Zone, as represented by the cross section near Mianchannun (Chichawatni to Khanewal), appears to be as described above, with a greater predominance of sand, and rare clay/silty materials. Except for a few local lenses, that too are a few feet thick, beds of hard rock, compact clay are rare in the area, rather beds of hard rock could not be found in BARI DOAB commands during 1954-62 test drillings. Gravels of hard rock are not found within the alluvium and coarse or very coarse sands are uncommon. According to pumping test results as reported by Bennett et al., (1967), lateral permeability results for the tests in and around the BARI DOAB area varies from 28.96 to 255.45 m/

day with an average of 84.09 m/day for these test [2]. Specific yield values as reported for four of these tests were 0.06 (Renala Khurd), 0.24 (Pakpattan), 0.04 (Harrapa) (however the value of 0.04 is very less to yield any groundwater in contrary to the wells installed in the area) and 0.31 (Arifwala) and vertical permeability values were 1.01, 3.95, 11.06 and 21.06 m/day, respectively for these four locations. Bennett (1967) has mentioned an average anisotropy ratio of 25 to 1, on whole Punjab basis [2].

The aquifer under Bari Doab irrigation system is characterized by its unconfined behaviour i.e. water is mostly derived from storage by drainage of pores. The watertable location in the aquifer is space and time dependent due to its unsteady state nature as result of varying recharge and discharge rates both with respect to location and time in the area. Most of the aquifer water is discharged by pumping out for irrigation and/or drinking in the area. Surface water is added to the unconfined aquifer through seepage from canals, watercourses and field irrigation losses or by surface infiltration due to rainfall events and rivers in the adjoining area.

The area is divided by partition in India and Pakistan. The area is a part of a vast stretch of alluvial deposits worked by the tributary rivers of the Indus. The parent material is of mixed calcareous alluvium derived from a variety of rocks during the Pleistocene period. The general slope of the area is mild towards the south-westerly direction with average slopes ranging from 1 in 4,000 to 1 in 10,000. The area lies in the Bari Doab between Rivers Ravi and Sutlej. Agriculture in the area is sustained through surface water supplies and pumped groundwater. Extensive groundwater development facilitated the increase in cropping intensity by addressing shortages in canal supplies and also lowering the watertable which resulted in declining soil salinity in the area. It is estimated that about 50% of crop water requirements are met by groundwater extraction. Bari Doab is therefore a very good conjunctive use farming system.

According to post monsoon 2014 situation, more than 59.1% area of Bari Doab was having depth to watertable (DTW) below 12 m, another 27.3 % was having DTW between 6 to 12 m [3]. Based on groundwater levels of 2002 and 2012, it was estimated that groundwater mining of 2.33 BCM (1.89 MAF) per year was taking place in Bari Doab [3]. Thus, only 13.59% area of Bari Doab was in normal range of DTW (< 6m). Keeping in view the continuous depleting conditions in Bari Doab, drainage Section, IWASRI studied the feasibility of "Developing Sukh-Beas as Potential Recharge Site during Wet Years for Bari Doab". For recharging the Bari Doab aquifer, the proposal is to divert the flood water from the Balloki-Sulemanki (BS) and Sidhnai-Mailsi-Bahawal (SMB) Link canals into the Sukh-Beas channel, depending upon flood water availability in the river system and the carrying capacity of the channel itself [3]. According to past figures and current watertable contour map most of high watertable areas lie towards head-end except Lahore where watertable is deep due to pumping for water supply, as shown in Figure 1. This high or shallow watertable towards head-end is due to high rainfall in the area.

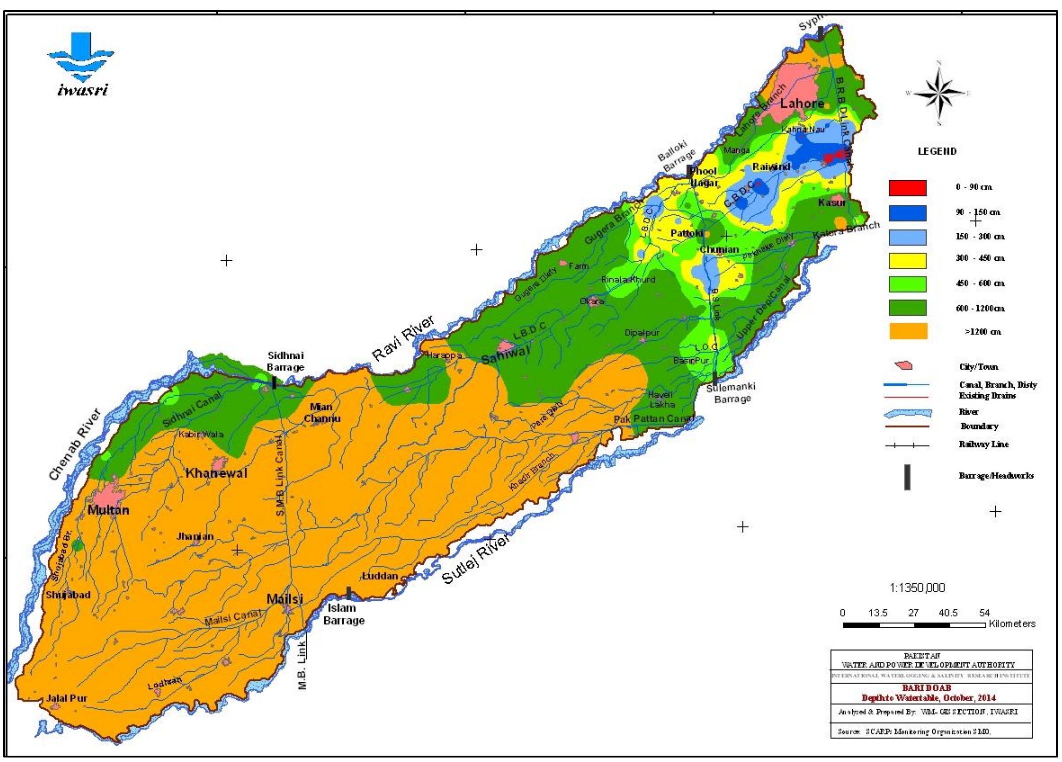

Figure 1: Depth to watertable map of Bari Doab for 2014.

1.2 Canal Water in Bari Doab

The most important and less dependable water resource is the canal water supply in the area. After the Indus Water Treaty in 1960 which gave India the water rights on the rivers Ravi, Beas and Sutlej, the Bari Doab falls under the Mangla Command receiving water through inter-river transfer links from the rivers Jhelum and Chenab, as shown partly in Figure 1 above. The irrigation water deliveries to the several canal commands in this large and complex national irrigation system are determined by the capacity of the physical infrastructure, i.e. reservoirs, barrages and inter-river link canals, as well as by legal agreements / and historic rules for the allocation of water. Cropping intensity in the Bari Doab area has steadily increased from the designed (60 percent) to the present about 200 percent. Canal supplies contribute up to 56 percent of the total supplies available at crop root zone. The other major contributor is the groundwater i.e. pumped by farmers themselves, however without any management by the government.

The groundwater supplies in many regions around the world are being rapidly reduced to meet growing irrigation demands and other needs in the face of diminishing surface water supplies e.g. USA and India [4]. The depletion of these groundwater supplies is expected to intensify as a result of climate change. These impacts are likely to be particularly severe in regions such as Bari Doab, where the groundwater is already being depleted at a very rapid rate. As the groundwater depletes the cost of pumping increases, and the risk of water quality deterioration also increases.

Nowadays, the potential of diverting surplus river flows has nearly been exhausted, and there are signs that surface water resource availability is dwindling, particularly in Bari Doab. This is due to decreasing online storage, population increase, and larger per capita water use with the passage of time. Until a few decades earlier, in addition to surface water utilization, increased groundwater use have provided a big boom for meeting additional water requirements. The exploitation of groundwater, mostly by private farmers, has brought numerous environmental and economic benefits to the agriculture sector in Pakistan. Share of groundwater is now almost half of all crop water requirements in the irrigated environment, at least in Punjab.

Groundwater is used for a variety of purposes in Pakistan, particularly including irrigation and drinking. A groundwater model is simplified representation of an actual groundwater system in the area. A range of computer codes (modeling software) exists for application to different problems. However, free software is only available from USGS in the form of MODFLOW and ModelMuse which is a Graphical User Interface (GUI) for MODFLOW.

1.3 Study Area Descrition-Canal Commands

This steady state groundwater model was developed in ModelMuse GUI developed by USGS, for irrigated areas of Bari Doab with a total area of 2.95657 Mha GCA. There are seven canal commands in the study are viz. Central Bari Doab Canal (CBDC), Lower Bari DOAB Canal (LBDC), Sidhnai, Depalpur Upper, Depalpur lower, Pakpattan and Mailsi as shown in the Figure 2 and Table 1 with salient features.

Canal	Year of Const.	CCA (000 ac)	GCA (000 ac)	Designed Intensity		Water Allowance		Discharge Capacity (000 cfs)	Length (Canal Miles)	
				Perennial	Non-Perennial	Perennial	Non-Perennial		Main	Total*
Lower Bari Doab	1913	1670	1789	60-67	66	3.00	3.30	9.20	129.90	1522.00
CBDC	1859	659	709	75-100		3.22		2.50		804.60
Upper Depalpur	1928	350	384		60		5.50	2.40	52.90	481.20
Pakpattan	1927	1049	1177	54-60	70	3.60	5.50	5.20	183.10	1143.20
Lower Depalpur	1928	612	654		60		5.50	4.00	6.40	779.00
Sidhnai Canal	1886	1017	1166	60-80	60	3.00	4.80	5.20	36.40	1145.20
Mailsi	data not available									

Table 1: Salient features of canal commands in BARI DOAB.

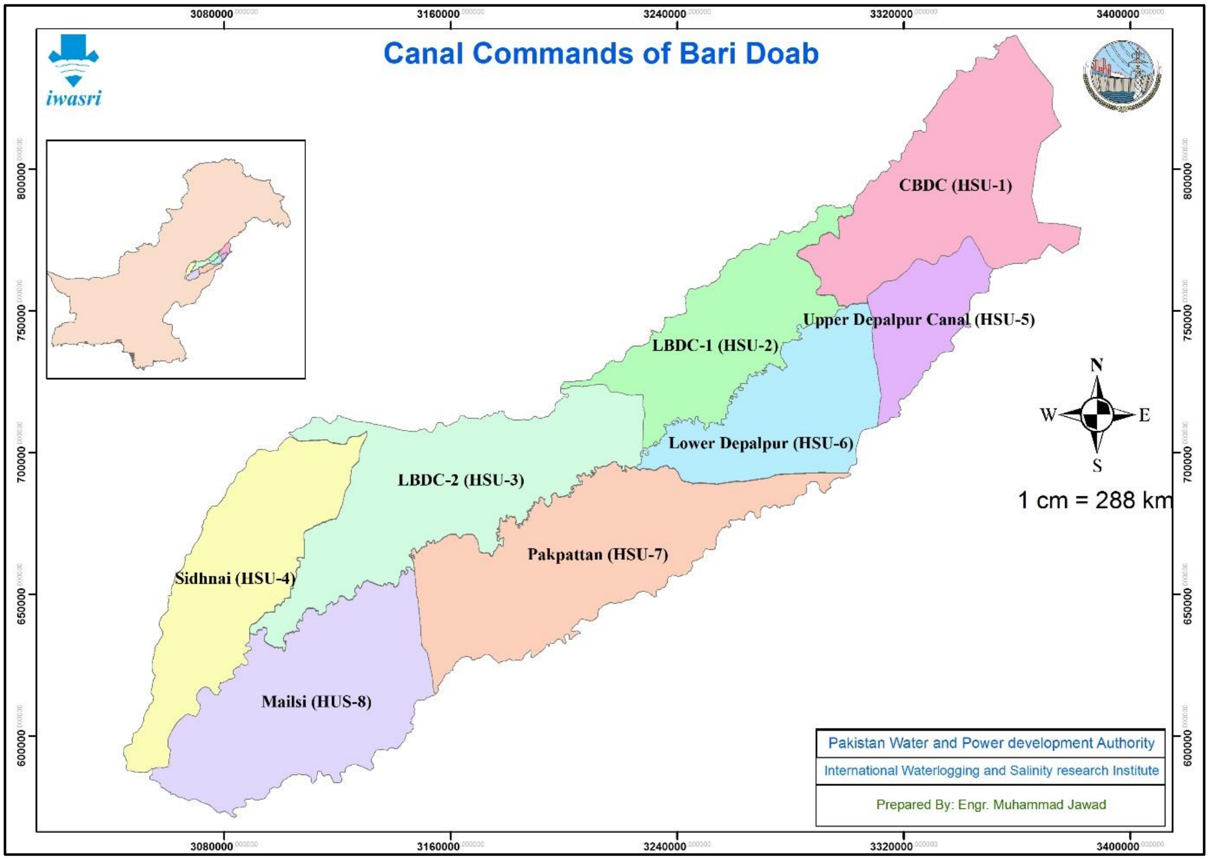

Figure 2: Assumed HSUs and canal commands in Bari Doab.

In each HSU meteorological & hydrological parameters were assumed to be uniform for the development of MODFLOW Model. All the geographical features were digitized using geographic coordinate system (WGS-1984) in ArcGIS using Google Earth, which were subsequently transformed to the projected coordinate system (Kalianpur India Zone I, 1962) for calculations of areas and other linear measurements.

The study area has associated limitations e.g., there is not any comprehensive data regarding aquifer characteristics, groundwater availability and irrigation water use by the farmers in such a big area; except poor estimation of annual groundwater pumping for agriculture purposes only by NESPAK and Basharat for LBDC only [5,6]. The study is based mostly on data collected from secondary sources e.g. aquifer characteristics, groundwater depth, and annual average irrigation supplies for last 10 years in canals.

1.4 Groundwater Modeling

Groundwater modelling is a helpful tool that can help analyze many groundwater problems in the area of interest. It begins with a conceptual understanding of the physical groundwater problem. The next- step in modelling is translating the physical system into mathematical terms. In general, the final results are the familiar groundwater flow and transport equations. These equations, however, are often simplified, using site-specific assumptions, to form a variety of equation subsets. An understanding of these equations and their associated boundary and initial conditions are necessary before a modelling problem can be formulated. This is also called conceptual model for the area.

Groundwater modeling, also called numerical modelling is a powerful tool to solve groundwater flow problems under varied and complex hydrogeological conditions and non-uniform recharge and discharge stresses. The flow domain is discretized into cells, nodes, and elements. The basic governing partial differential equation is transformed into a difference equation and applied recursively over the model domain. This results in a set of simultaneous linear equations which are solved with appropriate numerical analysis techniques e.g. using MODFLOW.

1.4.1 Finite Difference Method

There are basically two distinct forms for numerical modeling: Finite Difference Method (FDM) and Finite Element Method (FEM). ModelMuse uses FDM approach for discretization of area. Both of these numerical modeling approaches require that the aquifer be discretized into a grid and analyzing the flows associated within a single zone of the aquifer or nodal grid of the model. Finite difference methods convert ordinary partial differential (PDE) equations, which may not be necessarily linear, into a system of linear equations that can be answered by matrix formation. Modern computers can perform these linear algebra operations efficiently, which along with their relative luxury of implementation, has led to the widespread use of FDM in modern numerical analysis. Today, FDM are one of the greatest common tactics to deal with the numerical answer of PDE.

1.4.2 Mod flow

Groundwater modeling by using computer / numerical approach have become a widespread tool for analyzing various groundwater issues in the area of interest. Thus, much commercial software has become available in the industry. USGS had developed a modular groundwater modeling package in FORTRAN language under the name MODFLOW. The pre- and post-processors has made the software more user friendly, thus inducing a tremendous boost to the utility and adoption of the MODFLOW package. The USGS original software i.e. MODFLOW is a public domain now and have become the industry standard, while most commercial software in the form of GUI for application of MODFLOW model are licensed and available at a cost from various vendors. This commercial software differ mostly in the pre-and post-processing of the data capabilities for the MODFLOW model application.

1.5 Graphical User Interface

A number of the codes have Graphical user interfaces (GUIs), which help for MODFLOW in the creation of input files for the model code to read and for visualization of the model output. As a matter of fact, the basic concept of all models e.g. Visual MODFLOW, Groundwater Vistas, GMS, PMWIN is the same. There is no significant difference between them except software environment. ModelMuse is also the pre and post-processing platform developed by the USGS that implements MODFLOW model. However, this platform has a high performance due to its "design by objects" that optimizes the conceptualization of boundary conditions and other elements of the model, reducing the time needed to build the model and improving the interpretation of the output data of the area.

2. Methodology for Model Development

A steady state model for MODFLOW model was developed in ModelMuse, calibrated for Bari Doab and presented here. MF6 was used which is the latest version of MODFLOW and available in ModelMuse software. Model top was assigned from Google Earth Pro using TCX converter version 2.0, a free downloadable software, with 2317 points for elevation as shown in Figure 3, as well as various other objects used. Points were digitized freely but uniformly over the study area in Google Earth i.e. Bari Doab area on Pakistani side of the border. Interpolation was then used to specify the elevations throughout the grid. These data sets for the elevations can then also be used in the formulas for the upper and lower surfaces of “3D Objects” that define properties of aquifers i.e., layers of the model.

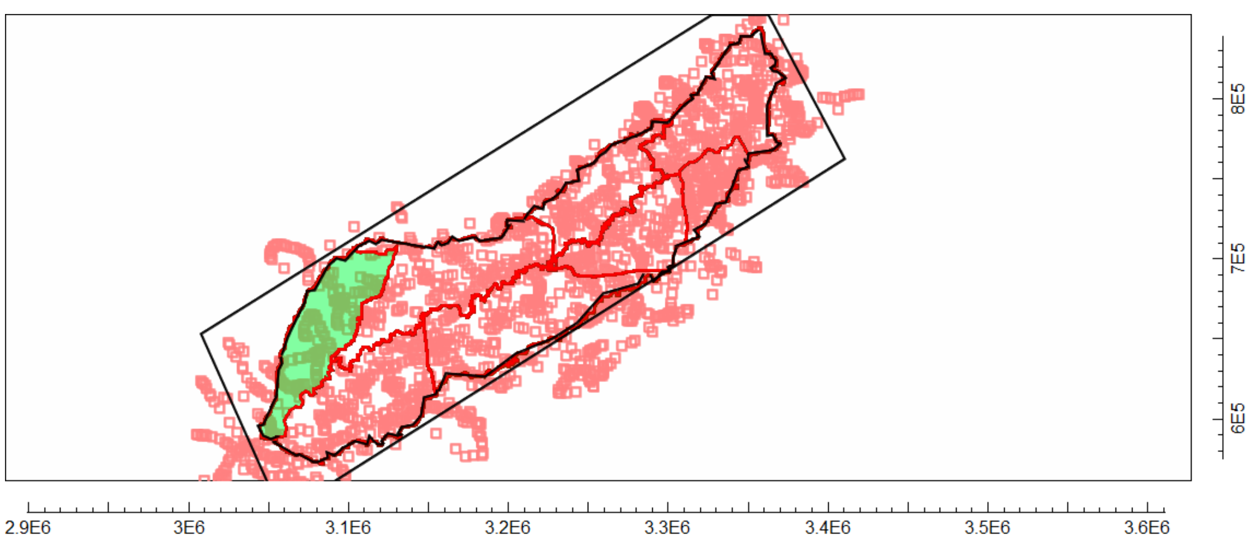

Figure 3: All objects in the model (Except the grid) as shown by ModelMuse.

2.1 Discretization

The aquifer was divided into three layers bearing thicknesses 30, 150 and 120m respectively (first layer represented upper soil with less hydraulic conductivity, wells were installed in 2nd layer, 3rd layer was to maintain laminar flow below the wells.), and eight HSUs. The area was discretized in to 1 km2 grid, with 1 km on each side, with 418 columns and 118 rows. In total, each of the seven canal commands was considered as single hydrologically similar units (HSUs) because the water allowance is same for the canal command under consideration, except LBDC where the command area was divided into two parts, each as one HSU because it is a bigger and long canal. Basharat and Jawad (2020) has given 0.0128 MAF as incoming groundwater from India and was assumed as incoming and outgoing regional flow in the model as

General Head Boundary (GHB) [7]. There are 49324 total cells in the model, whereas 42158 were active cells. The model is a steady-state model. Model top varied from +105 in the d/s direction to +216m in the u/s direction, top layer bottom varied from +74 to +188m, middle layer bottom varied from -75 to +36m, and lower layer bottom varied from -195 to -84m.

2.2 GIS Development for the Model

A full GIS was developed in ArcGIS and QGIS software was also used which is freely downloadable. First of all canal command areas were developed by digitization, keeping in view the canal command boundaries as used by Punjab Irrigation Department, so that HSUs concept could be followed in ModelMuse model. For this purpose QGIS was used. Groundwater pumping was applied in each cell of the 2nd layer, and recharge and ET to the top layer of the model, all confirming to canal command boundaries as shown in Figure 4. Rivers were also digitized from google earth and General Head Boundary (GHB) was applied at rivers Ravi and Sutlej surrounding West and East boundaries, respectively of Bari Doab, as rivers surrounding the area shown in Figure 1.

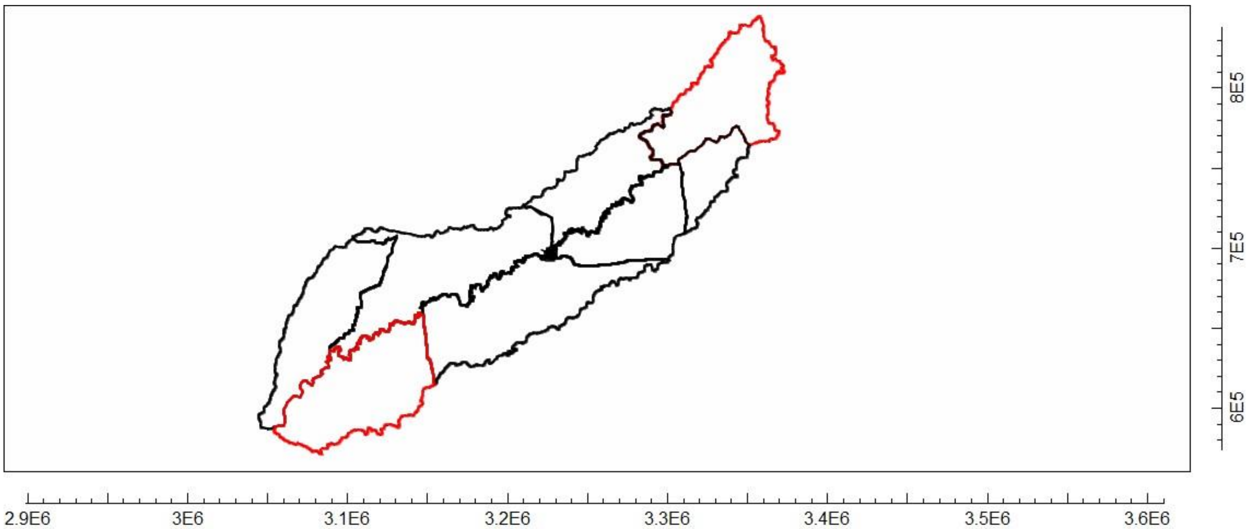

Figure 4: Showing canal commands and encompassing model boundary.

2.3 Data Handling in ModelMuse

ModelMuse assigns data values to data sets at cells in MODFLOW models using the following procedure.

• First, a default value is assigned to every node or element by using either the selected interpolation method, or the default formula for the data set.

• Next, each object that affects the data set is processed, and nodes or elements that are intersected or enclosed by each object are assigned values by using the object's formula for the data set. Each object replaces values assigned previously by the default formula or by a previous object.

• In MODFLOW 2–D data sets are typically used to define the upper and lower surfaces of grid layers rather than for defining objects that cross layer boundaries (Winsston R. B., 2019).

2.3.1 Assigning objects in ModelMuse

Objects were called in ModelMuse that were prepared in QGIS for Groundwater pumping and recharge, hydraulic conductivities of all the layers were based on the canal command boundary for easy handling. Also, active and inactive cells were based on Bari Doab boundary. Moreover, ET object was digitized in the form of a rectangle around the area of interest i.e. Bari Doab.

Observation wells were fed in Excel, transformed to csv file and processed in QGIS for importing in ModelMuse as shown in Figure 5. And the data was processed in Excel for groundwater elevations and converted to csv file for use in ModelMuse through object dialog box of ModelMuse.

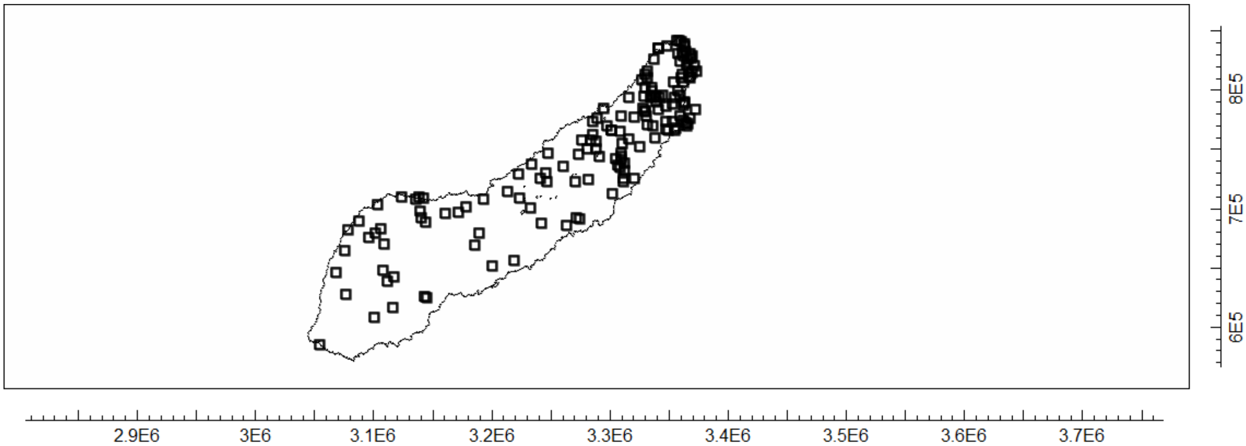

Figure 5: Showing observation wells and model boundary i.e. Bari Doab area (the squares represent observations).

2.3.2 Assigning Values to Data Sets in ModelMuse

Formulas and objects were used to assign the values as under:
Following were assigned using data sets;

• Kx was assigned using canal command objects. Ky was set equal to Kx and kz was set by formula i.e. by dividing Kx by 10, as the investigations carried out by WASID during the period 1961-63 [1].

• MOFLOW initial heads were assigned by formula i.e. upper aquifer bottom + 15.

• 2nd and 3rd layer bottoms were also obtained by subtracting the respective layer thickness from the respective upper layer bottom.

Following were assigned using boundary conditions under specified flux;

• Recharge was assigned to each cell by canal and rainfall calculated in Excel based on literature review and canal command boundaries. Pumping wells were also assigned to each cell, i.e. pumping groundwater recharged by canal and rainfall.

Following were assigned using boundary conditions under head dependent flux;

• Evapotranspiration was given in ETS package with ET rate of 4.0 mm/day and an extinction depth of 3.048037064 m (10 ft) applied to top layer only.

• General Head Boundary (GHB) was used assigning rivers of Ravi and Sutlej. Initially a value of 26000 m/day was assumed which was finalized to 26 m/day during calibration, as it is actually determined in the field for aquifer sediments [2].

2.4 Calculation of Losses to Groundwater

2.4.1 Excel Analysis of Canal Flows and Groundwater Recharge

Canal flows were analyzed in detail. For this purpose past 10 years data i.e. 2010 to 2019 was obtained from Punjab Monitoring and Implementation unit of Punjab Irrigation Department (PMIU, PID). Mean annual flow was calculated in m/year units and converted to model units i.e. m/day. Recharge to groundwater in the area is occurring from canal network seepage, watercourse and field application losses and rainfall. The recharge rates were assessed on HSU basis. PPSGDP made an extensive analysis of seepage rates from a wide ranged capacity of canals in Pakistan [8]. Seepage rates adopted therein were used for this study. Basharat has also used the same for his Ph.D. studies as given in Table 2 [6].

Component	Efficiency %	Remarks
Conveyance system	81.28	head to minor canals
Watercourse	75	80 % of this recharge to groundwater (WAPDA, 1980b and PPSGDP, 1998)
Field application	80	75 % of this recharge to Groundwater (WMED, 1999 and PPSGDP, 1998)
Overall	48.77	Available to crop consumptive use.

Table 2: Irrigation efficiencies adopted for calculation of recharge to groundwater, adopted from Baharat [6].

2.4.2 Watercourse, Field Application and Rainfall Losses

For the water diverted to the watercourse head, 25% were adopted as seepage losses within the watercourse (before entering the farm gate), and 80% of this was assumed as recharge to the groundwater. The irrigation application efficiency at the farm level was considered to be 80% and 75% of this was taken as recharge to the groundwater. The total recharge to groundwater from the watercourse and field application is 31.25% (20+11.25) of that diverted to the watercourse head. Rainfall recharge to groundwater in Bari Doab commands is also variable due to decreasing rainfall towards the tail. Ahmad and Chaudhry (1988) reported the rainfall recharge to groundwater as calculated in the Revised Action

Program (RAP) by using Massland's approach for the year 1977-78 for all the canal commands in Punjab province was applied here [6].

2.4.3 Sensitivity Analysis

Sensitivity analysis was also performed, recharge and pumping were found to be more sensitive here, particularly for river recharge.

3. Results and Discussions

3.1 Calibration

A necessary aspect of the model building process is the calibration phase. During this process, model parameters are adjusted until the model's application of historical field measurements is judged to be "reasonably good." It is then assumed that this constitutes sufficient defense to use the model to make forecasts and that those forecasts will also be reasonably good. Therefore, calibration of model was performed with the maximum number of observation wells observed in the area. The model was calibrated by varying values, e.g. the GHB was varied from 26000 m/day to 26 m/day, other parameters were also varied and the model discrepancy improved from 3.17 to 0.0%.

Calibration was done with 135 observation wells for which data was collected for post-monsoon 2019 by SMO of WAPDA. Excel was used as a tool for the assessment of the comparison. 1st graph as obtained, is shown in Figure 6, as shown below. Graph of the final and worthy considered comparison is shown the Figure 7, as prepared in Excel. Five graphs were prepared for judgments. Average, maximum and minimum differences between observed and simulated values calculated and found to be minimum for the calibration shown in Figure 7. Average, maximum and minimum differences between observed and simulated values were 0.0526643844444453, -16.991283 and 13.8919871, respectively.

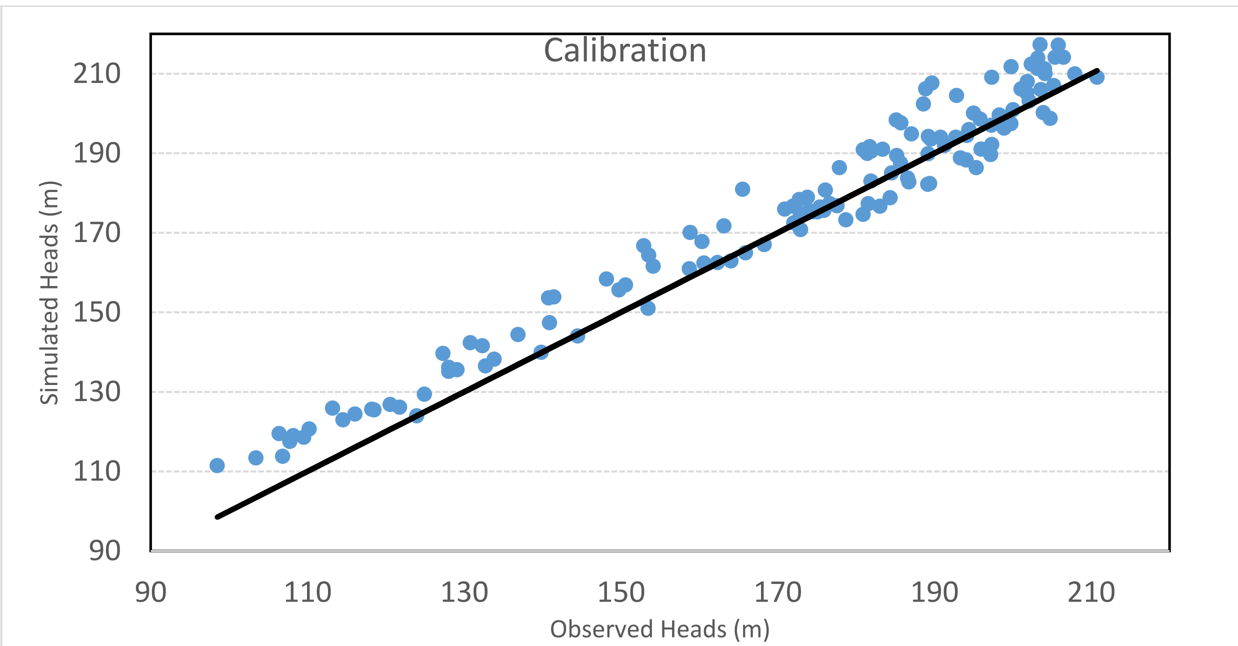

Figure 6: 1st Graph showing model calibration i.e. comparison between observed and model simulated values, prepared in Excel.

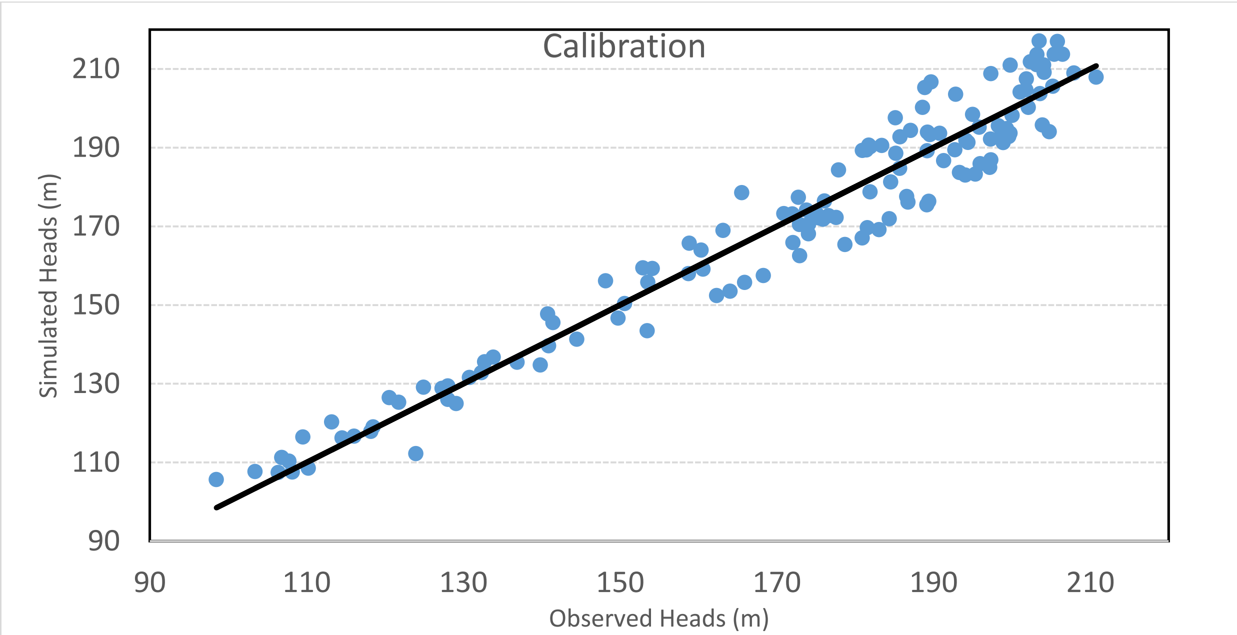

Figure 7: Final graph showing model calibration, prepared in Excel.

4. Conclusions and Recommendations

Following conclusions and recommendations are put forth.

- GUIs are more simple to apply for MODFLOW-based models;
- It is concluded that farmers are pumping 50 to 60 % higher than canal and rainfall recharge to groundwater from the aquifer.
- Canal water duty may be established in consideration of spatial variability of climatic parameters (rainfall and ET) as the climate becomes more arid in the South-West of Bari Doab;
- For canal water re-allocation, the most prudent way is to change the channel rotation operational times;
- It is evident from DTW contours that watertable is shallower near Ravi and Sutlej rivers, therefore, canal water be reallocated more towards center of Doab.
- Presently, the Government of Pakistan is lining the Muzaffargarh canal but it will not eradicate waterlogging in this area. Therefore, it is recommended to take groundwater modelling study in Muzaffargarh canal and reallocate extra water from this canal command to Bari Doab canals towards South of the area.

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Conflicts of Interest: There is no conflict of interest.

Ethical Responsibilities of Authors

Compliance with Ethical Standards was given due care during preparation of the manuscript by authors.

Ethical Conduct

Authors followed the rules of good scientific practice during manuscript writing.

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Data Availability: Data would be made available if requested by somebody.

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