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Numerical groundwater flow modeling of Kohat basin : An example from Himalayan fold and thrust belt Pakistan

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सार – उत्तर पश्चिमी हिमालयी फोल्ड और थ्रस्ट बेल्ट पाकिस्तान के अंत:पर्वतीय द्रोणी (बेसिन) (कोहाट उपद्रोणी) में वर्तमान और भविष्य में भौमजल की उपलब्धता और दोहन का मूल्यांकन किया गया। यह मूल्यांकन त्रि-विमीय (3D) न्यूमेरिकल भौमजल प्रवाह मॉडल को विकसित करके किया गया। गणितीय समकक्ष वास्तविक भौमजल प्रणाली को भौम जल मॉडल प्रस्तुत करता है। परम्परागत भौमजल प्रवाह मॉडलिंग प्रक्रिया का उपयोग जटिल जल भू गर्भीय प्रणाली के लक्षण बताने और पंपिंग और पोटेंशियल विदड्रॉल के फलस्वरूप मीठे जल संसाधनों के भविष्य का अनुमान लगाने के लिए किया गया है। इस गहन अध्ययन के लिए नहरों और नदी प्रवाह सहित समूचे बेसिन के भूभौतिकी, जल विज्ञानी और मौसम वैज्ञानिक आँकड़ों का उपयोग किया गया है। सीमित अंतर भौमजल मॉडलिंग प्रोग्राम (MODFLOW) का उपयोग क्षेत्र में 3D भौमजल प्रवाह की विभिन्न जल प्रबंधन रणनीतियों की जाँच करने के लिए किया गया। इसके परिणामस्वरूप भौमजल के उत्पन्न होने वाले क्षेत्रों के फलस्वरूप भौमजल के प्रवाह पैटर्न का अनुमान लगाने पर ज़ोर दिया गया जो प्राकृतिक प्रवाह से काफी मिलते जुलते थे। प्रेक्षण कूपों के हाइड्रोलिक हैडों का उपयोग स्थिर सिमुलेशन की आरंभिक स्थितियों के लिए किया गया। इस मॉडल से उत्पन्न किए गए हैंडों को 0.99 सहसंबंध समाश्रयण सहित 95 प्रतिशत कॉनफिडेंस अंतराल पर अंशशोधित किया गया। मॉडल का उपयोग ट्रांजिएंट स्टेट के लिए किया गया ताकि दिसंबर 2017 के वर्ष के दौरान हैडस् सफलतापूर्वक उत्पन्न किए जा सके। भौमजल के वार्षिक रिचार्ज के कम होने से जलस्तर में 25 मीटर की अचानक कमी आई जिससे आने वाले समय में जल की कमी के होने का पता चलता है। भौमजल के निरंतर निकासी होने और कुप्रबंधन से जल उपलब्धता की स्थिति के खराब होने का अंदेशा रहता है।

ABSTRACT. The present and future groundwater availability and exploitation were evaluated for an intermountain basin (Kohat Sub basin) of Northwest Himalayan Fold & thrust belt Pakistan by developing a 3D numerical groundwater flow model. The groundwater models attempt to represent an actual groundwater system with a mathematical counterpart. The conventional groundwater flow modeling procedure was followed to characterize complex hydrogeological system and predict future of fresh water resources in response to pumping and potential withdrawal. To support this study, geophysical, hydrological and metrological data of the entire basin including canals and river flow were used. The finite-difference groundwater modeling program (MODFLOW) was used for simulating the 3D groundwater flow in the region to investigate different water management strategies. The output is focused to predict the groundwater breed zone resulted in groundwater flow pattern, which closely resembled the natural flow. The hydraulic heads of the observation wells were used as initial conditions for steady state simulation; the model successfully generated heads calibrated with 95% confidence interval with correlation coefficient as 0.99. The model was also run for transient state which successfully generated the heads for the predicted year December, 2017. The groundwater withdrawal exceeding the annual recharge showed sudden drop of the water table by 25 meters, which demonstrated the future water deficiency. Continued withdrawal of groundwater and mismanagement showed possibility to lead critical condition on water availability.

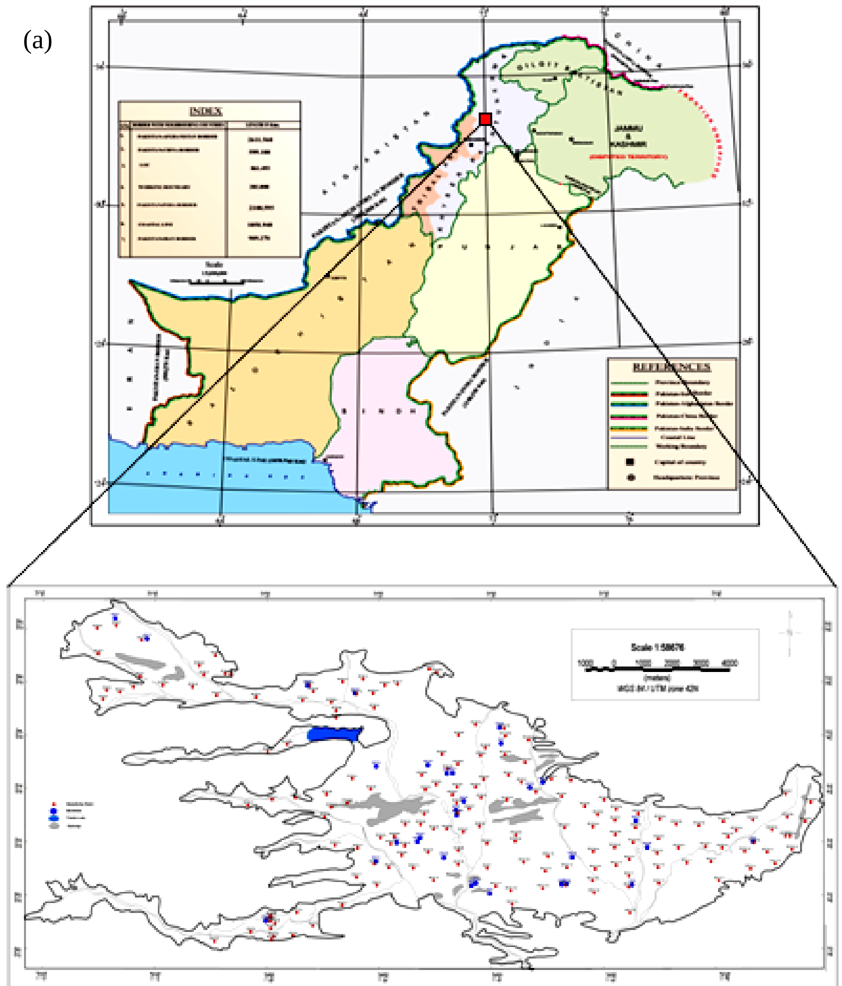
Key words – Numerical modeling, Groundwater flow, MODFLOW, Kohat basin, Pakistan.

1. Introduction

The estimation of groundwater flow in a basin by flow modeling can assist in predicting the future water scenarios. Intensive water resources development in the past decades had created large impacts on hydrological systems at basin-scales. Frequently reported negative effects are aquifer depletion, cease of base flow, drying of wetlands, degradation of riparian ecosystem and water quality and induced land subsidence and ground cracks. Currently, water resources management has been focused to consider a river basin as an integrated system where

(a)

(b)



Figs. 1(a&b). Location Map of Kohat Basin, highlighted in red rectangular box (a) with distribution of resistivity points (VES) in red color and wells in blue color. (b) Various canals are shown in grey color

interactions among surface water, groundwater, water resources use and effects on ecosystems take place. Decision-makers require adequate information on these interactions in order to formulate sustainable water resources development strategies (Kumar, 2006). To assess the future problems related to hydrology and hydrogeology of a basin, numerical modeling plays a vital role in the broad perspective of current and past hydrological setup. With rapid increases in computation capability and the wide availability of computers and model software, groundwater modeling has become a standard tool for professional hydrogeologists to effectively perform most challenging computational tasks. In this paper, a three dimensional numerical model using MODFLOW 2011 has been developed for Kohat basin, which is a well-known geological entity in Pakistan. While implementing the result, the aim is set to study the problems concerning the continuous drawdown in the level of water table in the study area. MODFLOW has the ability to analyze the spatiotemporal data and facilitate to conclude according to the pattern of current equipotential grid. It can iterate the random transfer and input data in the form of simulation to calibrate an unbiased result and forecast the future problems. The equipotential maps is used to analyze the surface hydrological conditions and the status of recharge /discharge to conceptualize the aquifer (Ashraf and Ahmad, 2008: WASY, 2004). The credit that governs on the result of simulation is to acquire the accurate and predicted results for the estimated area for arranged tenure. The tenure is regarded as the time for which the model is run to estimate the problems of drawdown in groundwater not depended on the aquifer boundaries (Naidu *et al*., 2012). It is very important to define the boundaries of basin despite of the layers chosen for aquifer flow estimation.

MODFLOW is used for planning and management of water resources in the study of hydro-geological framework. It provides strategies to compute the possible cone of depressions in specific zones of an aquifer (Varalakshmi *et al*., 2014). The main but non-obvious weak permeable zones can be pointed out in many basins using simulations model (Bridget *et al*., 2003). This type of modeling helps monitor the influx and out flux of water from an aquifer especially, in a demanding area like Kohat. The main purpose of this study is to focus the weak and impermeable zone for mitigating the water losses. In Kohat basin, Tanda Dam and its tributaries are mainly responsible for the recharge of groundwater. Groundwater is used in large extent for irrigation and household purposes. The channels in the basins are not fully equipped with present day irrigation system. Due to which large amount of groundwater is percolated to unidentified zones. During moderate climate conditions due to lack of rains, the area sometime met water needs which might cause the drought in certain middle altitude areas. A lot of private tube wells for extraction of groundwater is constantly producing cone of depression in the permeable formations. On the contrary, no proper drainage pattern is found in low elevated area where the improper use of drainage of groundwater is wounding the persistent water boundary. The cone of depression of groundwater table is located in low populated regions. These low and high cones of depression would lead to the future lack of groundwater (Kidwai, 1962). In Kohat basin, the major water supplies are from the groundwater and water from local reservoir (Tanda Dam). The flow of water from northeast forms part of the permanent water table through specific channels along the basin.

This paper focuses on assessment of groundwater in Kohat basin, Pakistan. Numerical groundwater flow modeling has been utilized to predict the future prominence of the groundwater in the study area. Groundwater withdrawal is more than the annual recharge which result in depletion in the water level day by day.

2. Background and hydrogeology of Kohat basin

Kohat Basin geographically lies in the northwestern side of Pakistan [Fig. 1(a)]. It is administratively situated in the Khyber-Pakhtunkhwa province of Pakistan at a distance of about 39 miles from Peshawar city and bounded to the north by Peshawar district and the federally administrated tribal areas adjoining Kohat and Peshawar districts. In the east, it is bounded by the Attock and Mianwali districts of the Punjab province; the south is bounded by the Bannu district and tribal area adjoining Bannu; and the west is bounded by the Kurram and North Waziristan agencies. The famous Indus highway passes through this area and the Indus River is flowing in the east of Kohat Basin. Tectonically the northern Pakistan region is undergoing subduction of the

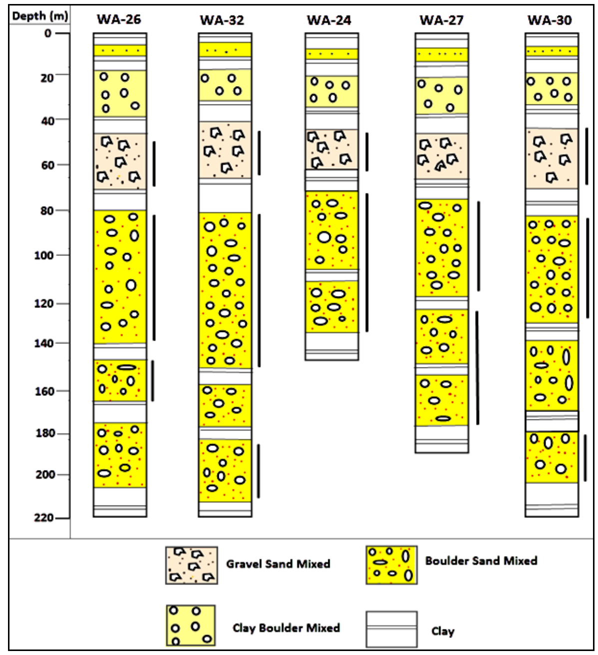


Fig. 2. Borehole lithologies of the study area

Indian continental plate below the Eurasian plate (Kazmi and Jan 1997; Shahzad *et al*., 2009, Searle, 1996). The folding of the relatively soft top layers has created the Himalayan mountain ranges. The Kohat Basin is considered to be good agriculture land suitable for cultivation. The depth of water required for irrigation is used more than the actual requirements which led to a rising groundwater table and a considerable part of the Kohat Basin is irrigated by water from Tanda reservoir (Bloemendaal and Siddiq, 1985). Fresh water is abundant in the Kohat Basin with water supply sources including Tanda Lake, Kohat Toi stream, some natural springs and other minor streams. Kohat Basin is irrigated using surface water which originates from various canals and streams as well as from groundwater in areas that have no access to canals and streams [Fig. 1(b)]. The study area is a part of a large intermontane basin where sedimentation has taken place from weathering and erosion from the surrounding mountain belts (Burbank 1983; Tahirkheli 1985; Bloemendaal and Sadiq 1985). The mountain ridges surrounding Kohat Basin show a general east-west trend, with the maximum height of the mountains to the north-west of the Basin is at 2,716 meters above mean sea level, while those on the southern side reach have a maximum height of 655 meters. The alluvial basin covers approximately 2973 km^2. The thickness of the saturated alluvial fill ranges from several hundred meters in the central part to a negligible amount in the valley along the western boundary. The alluvial fill in the central part of the basin is the main groundwater reservoir for the area. About 40% of this alluvial fill consists of well sorted, thick gravel layers. Top layers are mostly clayey and may cause confined aquifer conditions (Kruseman and Naqavi, 1988).

The boreholes (Fig. 2) indicate that the sedimentation patterns of the alluvial deposits of Kohat basin are extremely erratic and heterogeneous. Considerable differences in lithology, both horizontally and vertically, occur from place to place. The alluvial fan sediments consist of mixture of gravel, boulder, sand and clay in varying proportions. The flood basin deposits are mainly clays and fine sands. The sandy deposits are predominantly the product of erosion from the main boundary thrust in the north of the study area.

3. Methodology

The fundamental law which provides the basis of groundwater flow model is the Darcy's equation, which can be written as:

$$Q = -\mathrm{K}A\frac{dh}{dl} \qquad (1)$$

where, Q is the flow rate through porous media (m^3/sec or m^3/day), A is the cross sectional area (m^2) perpendicular to the direction of flow, K is the proportionality constant, represents hydraulic conductivity (m/s or m/day) and dh/dl is the hydraulic head difference over the path of length *l*, also known as hydraulic gradient.

The governing 3-dimentional groundwater flow equation based on the continuity of flow and Darcy's equation is given by:

$$\frac{\partial}{\partial x}(\mathrm{K}_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(\mathrm{K}_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(\mathrm{K}_{zz}\frac{\partial h}{\partial z}) - Q = S_s\frac{\partial h}{\partial t} \qquad (2)$$

where, $\mathrm{K}_{xx}\,\mathrm{K}_{yy}\,\mathrm{K}_{zz}$ = hydraulic conductivity in x, y and z direction, respectively which are assumed to be parallel to the major axes of hydraulic conductivity;

h = Piezometeric head;

Q = Volumetric flux per unit volume, which represents source or sink.

S_s = Specific storage co-efficient which can be defined as the volume of water that is released from storage of porous media per unit decline in head per unit volume.

3.1. *Conceptual model*

A conceptual model is a simplified and schematic representation of a hydrogeological system to be modeled. Conceptual model is based on detailed information and understanding of a true hydrogeological condition which is derived from the field investigations and regional groundwater data. For the present study area, data were collected from Pakistan Water and the Power Development Authority (WAPDA) hydrogeological department, Peshawar. The conceptual model is developed by using geological and hydrological framework, areas of recharge and discharge, hydraulic characteristics, initial and boundary conditions, spatial and temporal dimensionality, etc. The development of the conceptual model is also considered the lateral and vertical extents of the subsurface layers and the structure of the lithological units in the alluvium cover. The hydraulic properties of the subsurface formations play an important role in the groundwater flow. The hydrogeological system of the study area is modeled as multi layered. The layers have erratic thickness in the investigated area. The alluvial deposits comprised of mixed facies of boulder sand, gravel sand, clay with some boulders, sand and mainly clay. These layers have been assumed for the conceptual model and the main source of recharge is precipitation and natural springs. Kohat Toi and another small stream on the east side of the study area are considered as constant boundaries. Based on the lithological variations (Fig. 2), in addition to other hydrogeological and hydrological conditions, the conceptual model for the area is developed. The aquifer is divided into three layers on the basis of subsurface lithologies. The first layer is boulder mixed with sand having bottom at 440 meters elevation and 3rd layer is gravel sand having elevation 375 meters above mean sea-level.

3.2. *Model description*

The model designed for groundwater flow system of Kohat Basin covers approximately 2000 km^2 in the model domain. The vertical extent of the model is based on the three hydrostratigraphic layers as defined in the conceptual model. The model grid is oriented in north-east to south-west direction, which follows the natural topography of the study area. MODFLOW 2011 built-in finite difference scheme is used to simulate the groundwater heads by using mathematical simulation. In finite difference method, the orientation of the model grid should be such that minimum number of nodes lies outside the model domain. The outside nodes are defined as inactive nodes which do not take part in the simulation of groundwater flow (Anderson & Woessner, 1992). In order to simulate the groundwater flow of Kohat Basin, the model was designed with grid size of 1.6 km both *x*

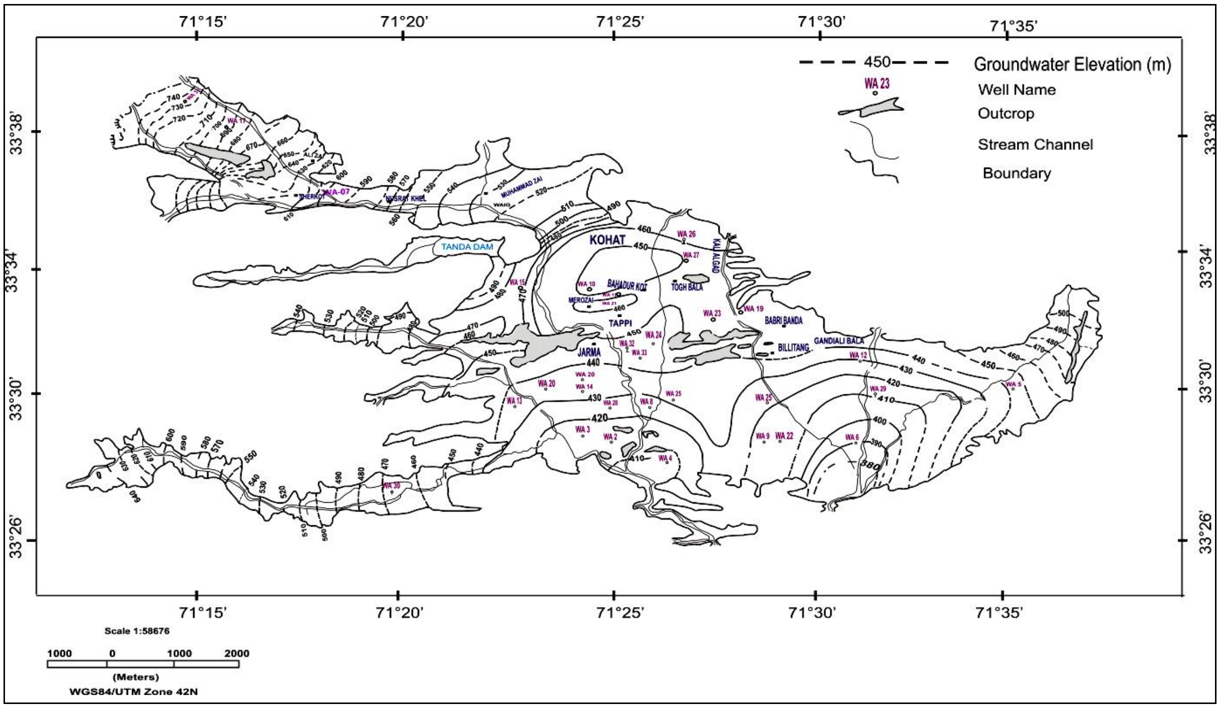


Fig. 3. Water table map of the study area for the year 1978

TABLE 1

The values of hydraulic conductivity, specific yield, storativity and porosity

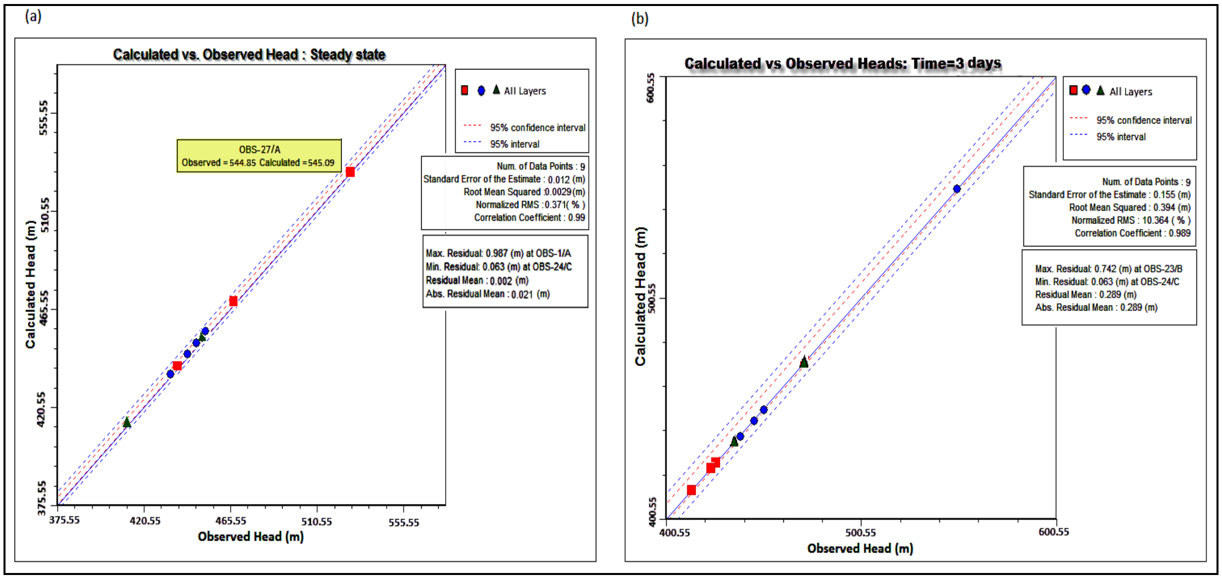
Layers		1			2			3		
Properties		K(m/d)	S_y	Porosity	K(m/d)	S_s	Porosity	K(m/d)	S_s	Porosity
Zonation	1	110	0.15	0.3	55	0.012	0.33	135	0.025	0.412
	2	170	0.07	0.3	76	0.001	0.33	156	0.017	0.412
	3	30	0.3	0.3	26	0.025	0.33	25	0.027	0.412

and *y* direction. The number of grids for the study area thus consists of 80 columns and 120 rows, having a total number of cells of 11700 in which the active cells are 8200 and inactive cells of 3500. The grid size was refined further near to the pumping wells and natural features such as, Kohat Toi stream. Pumping wells lie mostly in the center of the model domain and streams on left and right within the active zone. The model boundaries play an important role in simulation of groundwater flow. For this purpose, natural boundaries of the study were considered as the model boundary. Kohat Toi stream on the left side (western side) of about 35 km long and 0.1 km wide and stream on the right side (eastern side) of length 21 km and width 0.09 km were assigned as constant head boundaries. The model input parameters as in Table 1 were used for simulation.

3.3. *Hydraulic characteristics and model calibration*

To design a model for groundwater flow simulation of an aquifer, hydrological data and understanding of properties of water table, hydraulic conductivity, etc. play an important role. The estimation of the intrinsic permeability and depth of the media is thus processed for the simulation runs. In MODFLOW environment, the following equation is considered for computation of hydraulic conductivity through the layers of the media:

$$K_h = \frac{\sum K_{hi} d_i}{\sum d_i} \tag{3}$$

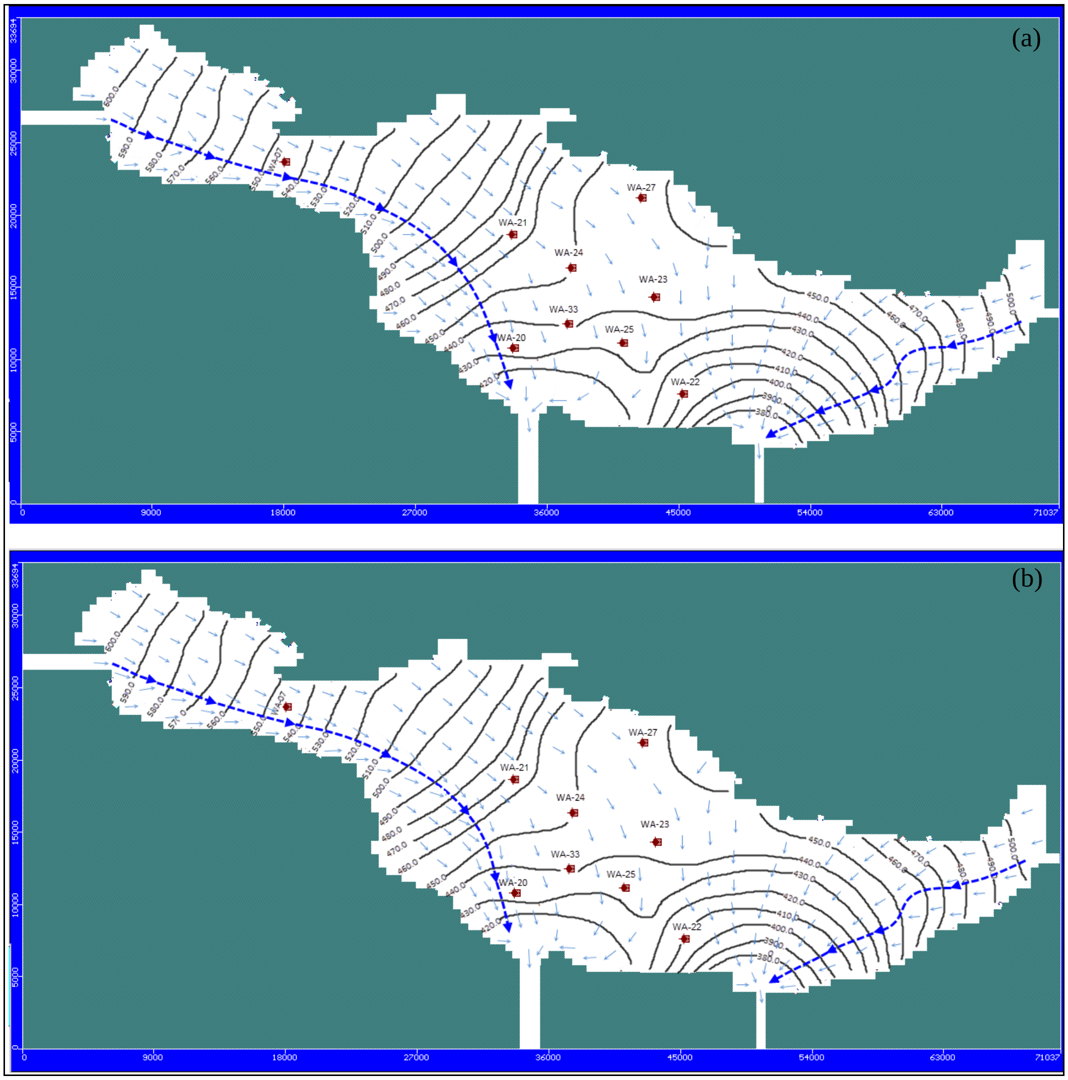


Figs. 4(a&b). 1:1 plot of computed and observed heads with 95% confidence interval (a) for steady state simulation and (b) for non-steady state (transient) simulation

where, K_h, K_{hi} and d_i are respectively, hydraulic conductivity, intrinsic permeability and depth of the medium.

Based on the available data, three hydraulic conductivity zones are recognized and marked where in the variability ranges from 30 to 150 meters/day. Model calibrations involve changing the values of model's input hydraulic parameters to match the field conditions with some acceptable standard criterion. For model calibration, it is important to note that field conditions at a site should be properly characterized. Lack of information and site characterizations may result in cases that do not prevail in actual field conditions. In steady state simulations, with the passage of time, no changes in hydraulic head for the field conditions are observed; whereas, transient simulations involve variations in hydraulic head. Model calibration should be based on the comparison between simulated and field conditions of hydraulic head data, water mass balance, hydraulic head gradient or groundwater flow direction. Steady state conditions are generally taken to be historic conditions that existed in the aquifer before significant development has occurred such as, inflows are equals to outflow and there is no change in the aquifer storage. By trial and error from sequential runs until the match between the observed and simulated head contours obtained, the hydraulic conductivity values for the present Kohat Basin were estimated. The accuracy of the computed water level was judged by comparing the mean error, mean absolute and root mean square error (Anderson & Woessner, 1992). The root mean square (RMS) error represents the square root of the sum of square of the differences between calculated and observed heads divided by the number of observation wells. The steady state calibration are based on pre-development potentiometric surfaces of the year 1984, which was considered to be the period when groundwater system was apparently in steady state conditions. The calibrated model was achieved by PEST (Parameters estimation) (Doherty, 1994). Unless there are huge number of sources of water nearby (stream, Lake or River), the true steady state is rarely achieved in reality (Akhtar *et al*., 2006). The hydraulic heads of April 1984 from nine observation wells were used as initial conditions for steady state simulation.

The steady and non-steady states of the calculated heads versus observed heads [Figs. 4(a&b)] show that all the heads are constrained to 95% confidence interval, which is the higher limit of the normal distribution of mean and standard deviation. Maximum and minimum residual errors in the calibration are 0.987 and 0.063 meter at OBS-1/A & OBS-24/C, respectively. The mean residual and absolute errors for the steady state calibration are 0.002 and 0.021 meter, while RMS value is 0.0029 meter with standard error of estimation 0.0012 meter and correlation co-efficient 0.99. The analysis of steady state equipotential surface map of the study area follows the regional groundwater flow trend, which shows that groundwater drains in the south of Kohat Basin. The continuous drawdown would certainly affect the release of water in the form of cone of depressions; while less rainfall in the area may cause these cone of depressions around the well. In steady state simulations, the hydraulic



Figs. 5(a&b). Variation of specific yield in the modeling domain: (a) 0.07 to 0.3 for layer-1, (b) 0.017 to 0.027 for layer-3 based on the data of the year 1984

heads are time invariant and the specific yield or storativity has no effect on the flow process. The specific yield and storativity values of 8 wells derived from the pumping test data analysis and literature (Anderson & Woessner, 1992) are used and calibrated during transient simulations by comparing simulated heads with observedheads of wet season. Transient state calibration was carried out to investigate the effect of storage parameters *i.e.*, the storativity and specific yield on the equipotential surfaces and also to evaluate the impact of groundwater withdrawal by pumpage. Using the hydraulic heads of 10 observation wells, the model was calibrated for period of 3 days (72 hours) pumping for transient (Non-steady state). The data, used for steady state simulation as initial conditions, were used for transient state as well. The results of calibrated model for the non-steady state simulation [Fig. 4(b)] showed standard error of the estimate is 0.155 meter and RMS of 0.394 meter.

3.4. *Initial and boundary conditions*

The use of incorrect initial condition introduces errors in the calculation. Strictly speaking initial heads in a transient simulation should be the result of a transient simulation (Middlemis, 2000). For steady state simulation, the field data such as, pumpingtest, water levels, monthly precipitation and hydrogeological framework were used as initial conditions, while the output of heads corresponding to a steady state solution with average values of inflows and outflows were used as initial conditions for transient

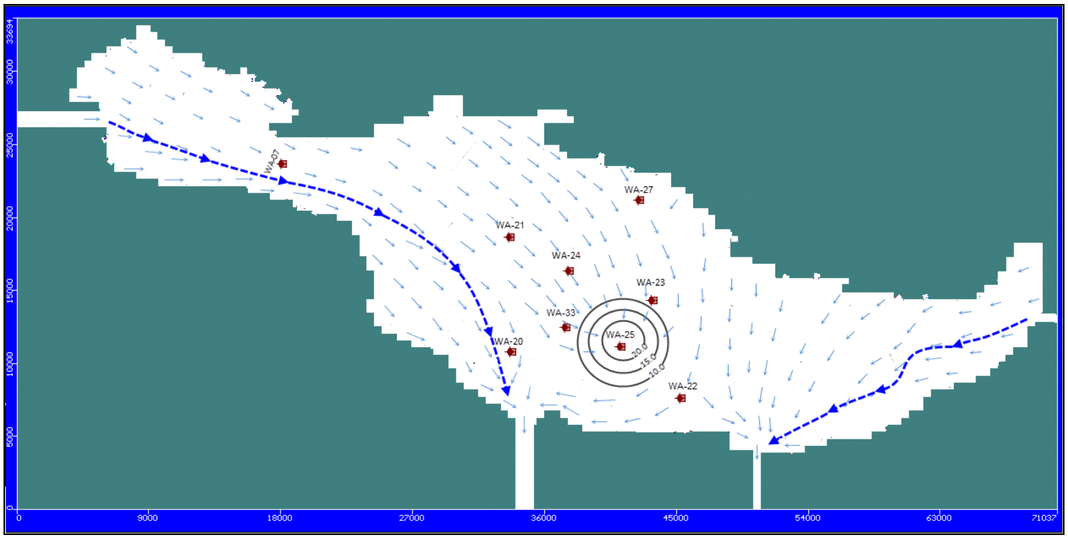
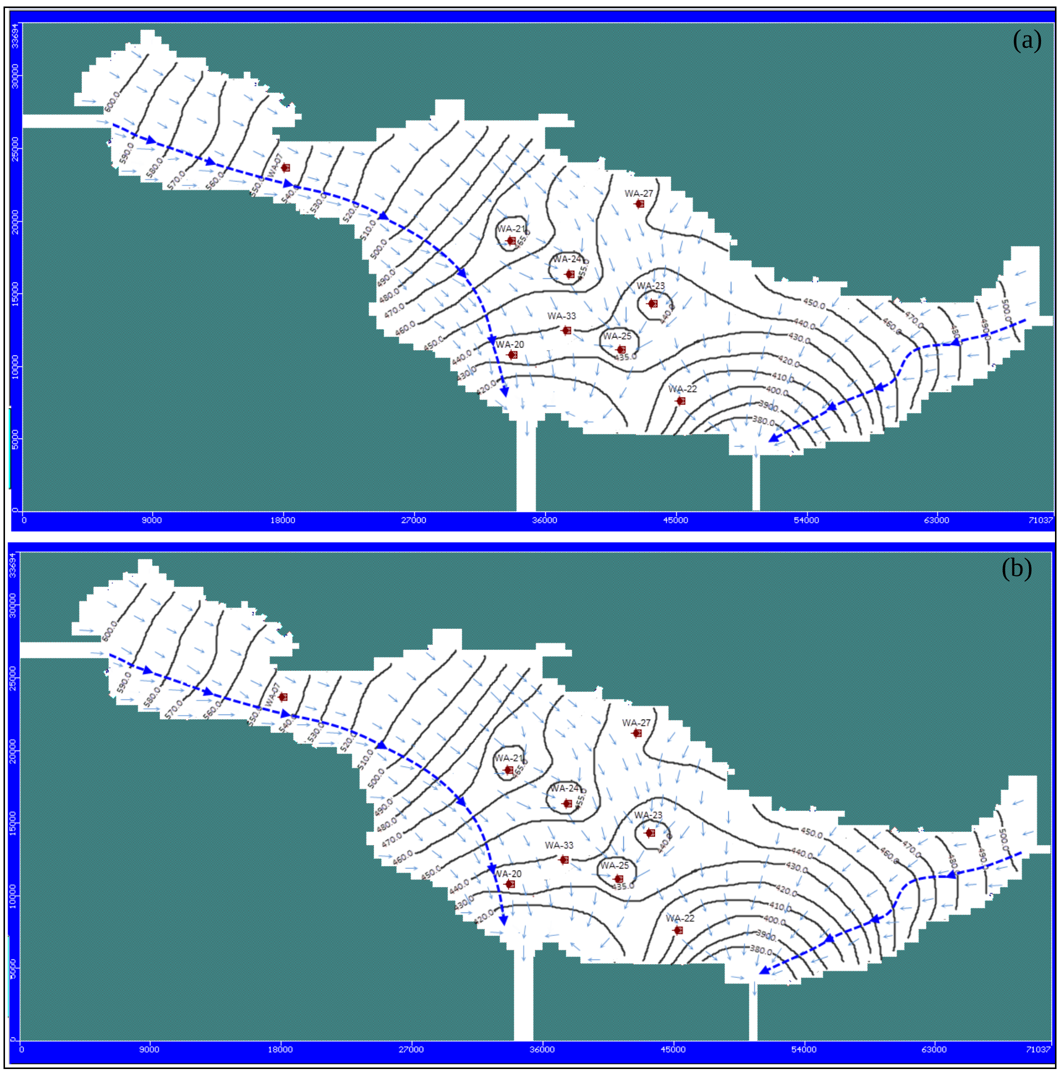


Fig. 6. Plot of groundwater flow direction of the year 1984 that showed direction is towards the WA-25



Figs. 7(a&b). Maps showing equipotential lines of the study area. The drawdown captured for (a) layer-1, (b) layer-3 for the active wells no. WA-21, WA-23, WA- 24 and WA-25 for the year 1994

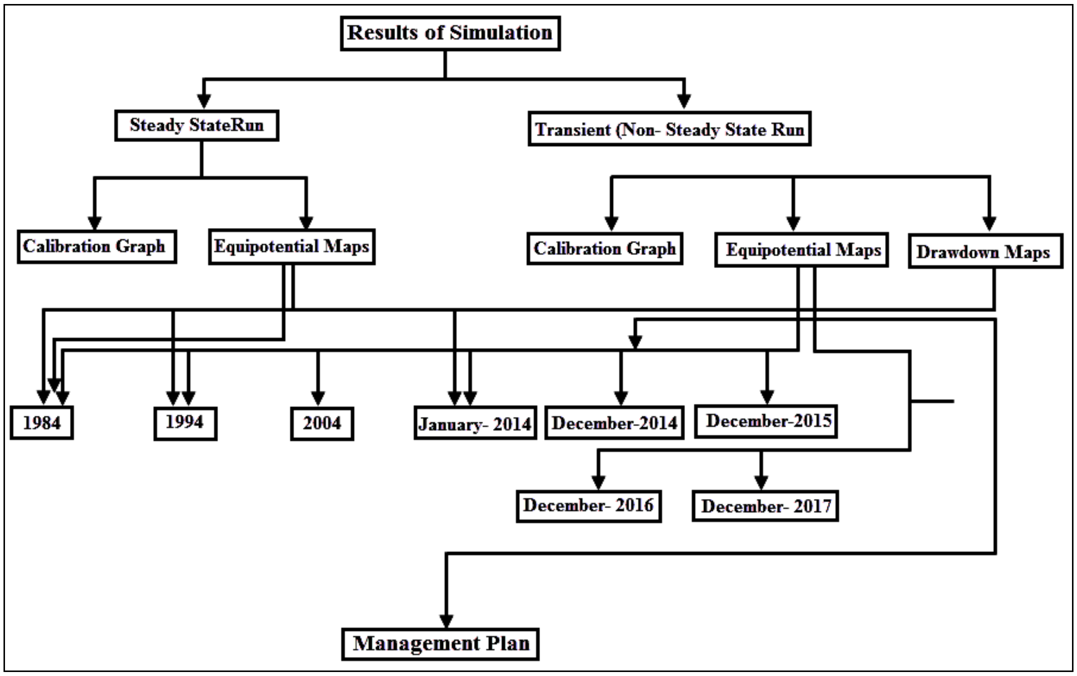


Fig. 8. Flow diagram of the strategies adopted for numerical flow modeling of the study area

(non-steady state) simulations (Rushton and Wedderburn, 1973).

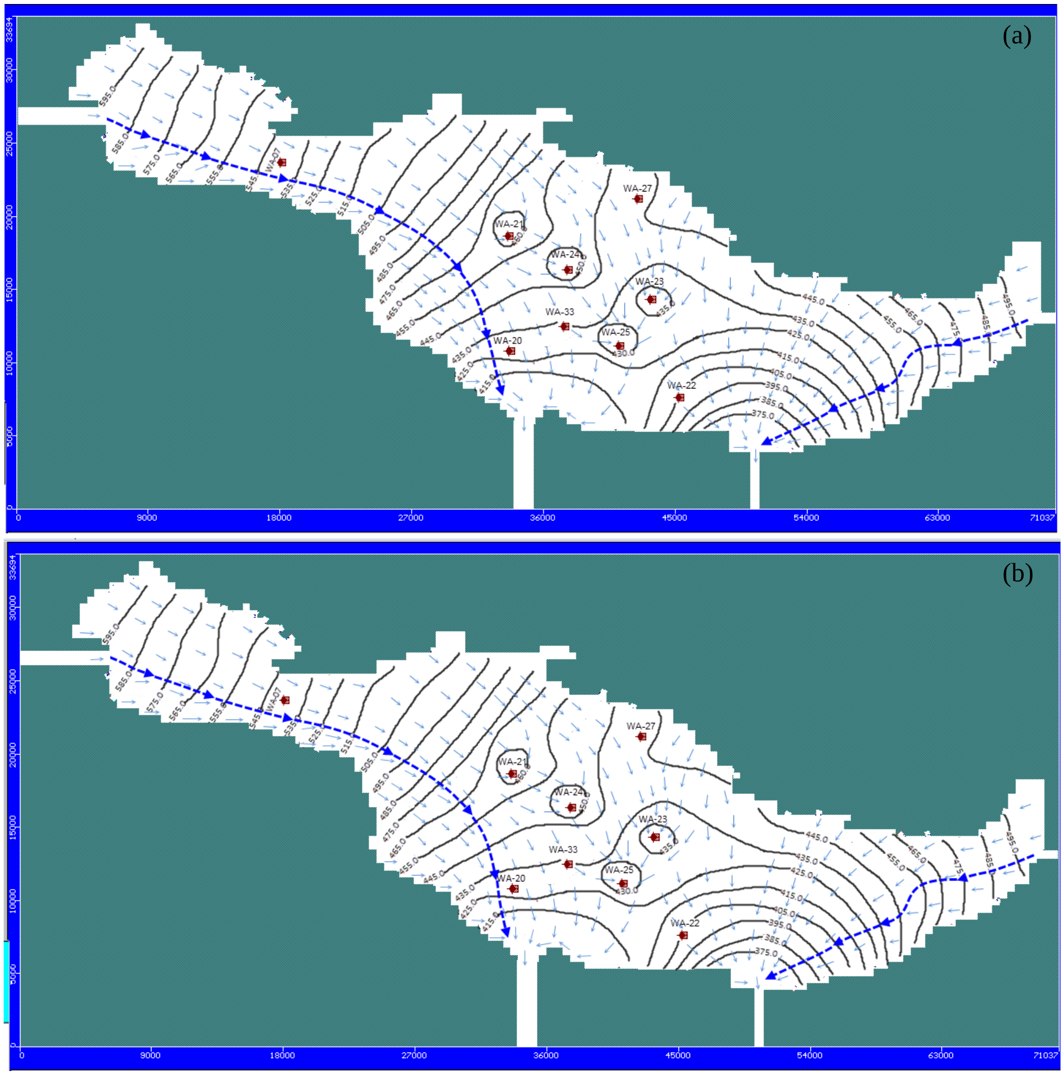
Boundary conditions are the essential component in groundwater flow modeling (Midllemis, 2000). The boundary conditions include: fixed potential (Dirichlet type), impermeable (Neumann type) and variable flow (Cauchy) (Rushton and Redshaw, 1978). The boundaries embedded in the program simulate the condition of impermeable (no flow) boundaries (Neumann condition), if not specified otherwise. For assigning the boundary conditions of the aquifer system, water table contour map for the year 1978 was used as in Fig. 3, which indicates the groundwater flow direction from northwestern part of the modeling area towards the south.

The basin is constrained to Tanda dam in the Northwest to a small lake in the east. The irrigation water is being supplied from Tanda Lake through canals; which are spread over the fields by overland flooding. From the world wide experience, it is known that irrigation water with overland flooding can amount up to 50 per cent of the water supplied. Part of the water will reach the groundwater table through percolation.

4. Modeling results

The framework of the conceptual model is implemented on the field data to find out the errors as residue of the water head of respective wells. The model is simulated using the data from 1984-2014 to determine the transient groundwater flow for the period of 2017. The flow diagram of modeling framework is given in Fig. 8. It is deduced from the modeling results (Figs. 5-9) that the water table is constantly declining due to extraction of fresh water from different sources in the basin areas. Simulated heads for the calibrated steady state condition are in Figs. 4(a&b). Hydraulic gradients are more pronounced in the upper land areas, especially immediately upstream and downstream of Kohat Toi River. The pattern of water level contours and groundwater flow predicted from the calibrated model are qualitatively similar to the water table map [Figs. 5(a&b)] used for developing conceptual model of Kohat Basin.

From the calibrated results [Figs. 5(a&b)], the variations of specific yield are found to be from 0.07 to 0.3 for layer-1, 0.001 and 0.017 to 0.027 for layer-2. The depleted values are due to the complex alluvial deposit, which encompasses low and high permeable beds. The drawdown in the wells indicated that the pumping from the wells had constantly took place that has depleted the groundwater levels (Fig. 6). The transient flow outputs in the form of equipotential lines showed that well WA-25 has been influenced by a depleted groundwater level. The continuous rate of groundwater withdrawal would obviously affect the stream base flow. The transient model run provides an insight of those significant periods that are

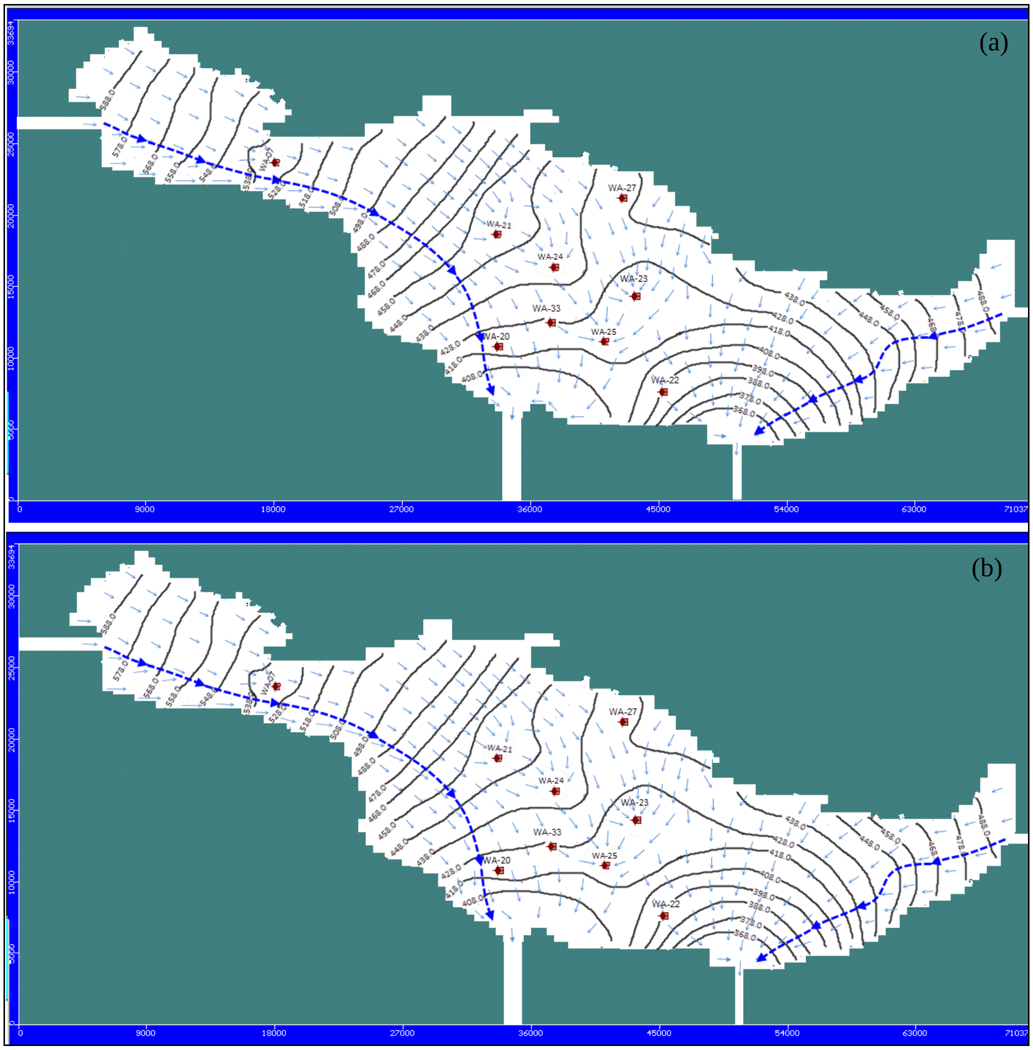


Figs. 9(a&b). Maps showing equipotential lines of 4 active wells in the basin for the year 2004: (a) for layer-1 and (b) for layer-3 that suffers most due to less percolation at well WA-25

fascinated by steady state results in the form of long term averages (Harbaugh, 2005). As a subroutine of 1984, the model is iterated for the calculation of heads with a time lag of 10 for the period 1984-2014.

The simulated run of the year 1994 [Figs. 7(a&b)] showed that the direction of equipotential lines is from northwestern towards eastern corner of the basin. In the respective year, four wells were used for pumping and the drawdown observed was 20 meters in the well WA-23 [Figs. 7(a&b)]. The simulated results of the different layers showed that the excessive drawdown of groundwater levels is not merely due to high demand of water for irrigation purpose. The discrimination of the disturbed cone from the rest of the flow direction can enhance the groundwater flow velocity mainly towards the cone of depression. The groundwater velocity is found higher near the well from adjacent zones around the well [Figs. 7(a&b)], which is different than pattern in other areas. The similar pattern is also seen for the layer-3.

The remarkable decline in permanent groundwater table for the period 2004 [Figs. 9(a&b)] is due to high rate of groundwater withdrawal for the domestic purposes or may be due to lack of recharge and high evapotranspiration. Although the water table is shallow in the northwestern sector, as compared to southern part having the hydraulic head of 495 meters, however, the turnouts of the wells (WA-21, WA-23, WA- 24 and WA-25) have fluctuated from nominal to a pronounced value in the study area. Flow vectors with long tail around the well WA-24 and WA-22 showed the steep and rapid

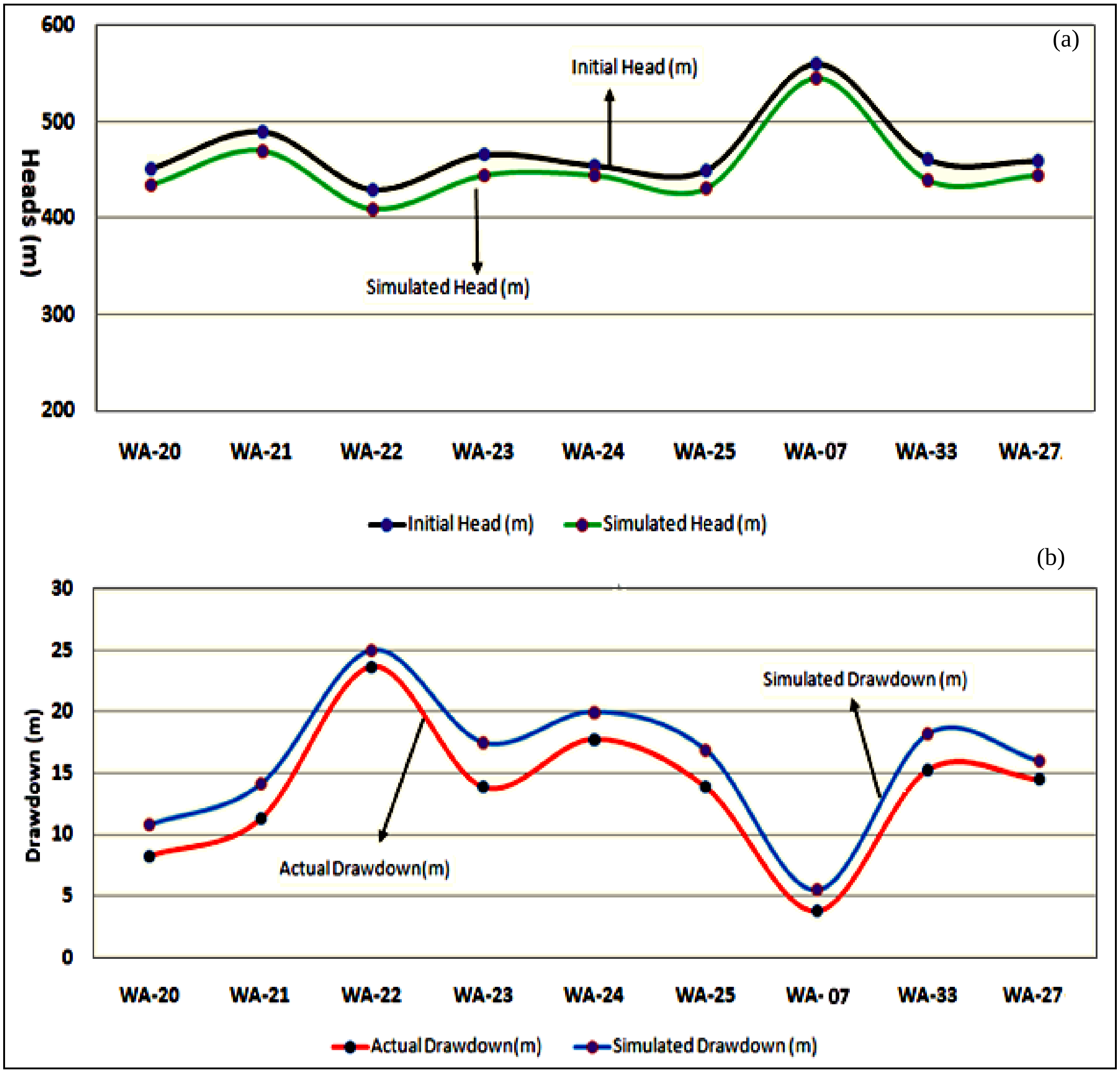


Figs. 10(a&b). Simulated results of equipotential lines; (a) for layer-1 and (b) for layer-3 of the study area for December- 2017, in which all 5 wells accomplished to problems related to hydrogeological conditions

flow pattern in layer-1and for same scenarios of layer- 3 [Figs. 9(a&b)]. Figs. 10(a&b) showed the drawdown that varied from 442 to 412 meter, which is healed by the Tanda Dam operated during the same year. The drawdown in the same area is due to the large extraction of groundwater by the wells WA-23, WA-24 and WA-25. The main purpose of this perspective is to evaluate the extent depletion of groundwater table and to suggest the possible remedial measures to combat the future hydrological problems in the study area.

5. Management scenarios

Water demand for domestic and industrial uses in the Kohat Basin Pakistan increased due to population growth in the region. Groundwater management may require coordination for replenishment and withdrawal of water to achieve the long term sustainability for water supply. The model was run to predict scenarios upto December, 2017 based on the historical hydrogeological data. The predicted scenarios are analyzed to resolve the problems of depleting groundwater levels in the concerned area. From Figs. 10(a&b), it could be seen that the equipotential lines are not steeply declined but has a smooth interval of 0.5 meter; whereas the hydraulic head has maximum and minimum values 590.5 and 370.5 meters, respectively. This is due to considerable extraction of groundwater with recharge source from one small dam only. There are a number of small streams and lakes in the area, which are seasonal in nature (Ghazanfar *et al.*, 1990). The effects of those lakes on groundwater cannot be overruled.



Figs. 11(a & b). Results of actual versus simulated drawdown for period 2004

6. Model simulations and predictions

After the successful calibration of the transient state setting, simulation runs for 10 years were performed to investigate the effect of changes in flow pattern due to groundwater withdrawal. The flow system was simulated for pre-pumping and pumping stresses to examine the changes in the groundwater flow scenarios due to the groundwater abstraction. These simulations were based on the available hydrogeological data and also hypothetical data from 1984 to December, 2017 [Figs. 10(a&b)]. The comparisons of variation of hydraulic heads between the actual and simulated are shown in Figs. 11(a & b). For the simulation run, the recharge rate in each stress period was considered in accordance with water supply to the canals, annual recharge rate of rainfall, groundwater extraction from wells and stages of streams. During these periods, the groundwater level varied from 600 to 380 meters above mean sea level in the entire numerical groundwater flow model. Major fluctuations of groundwater levels were seen between 470 and 420 meters within the entire area and groundwater flow is observed to be from both the sides of the study area. The north-western and eastern sides have steep slope, which indicates groundwater flows are mainly from these two zones and drain into the south. The strategic plan (Fig. 8) that consists of outputs from the steady and transient state, showed that groundwater levels declined continuously till December 2017 and a large decline of approximately 30 meters is observed.

7. Conclusions

Groundwater model has become a frequently used tool for hydrogeologists to carry out various tasks concerning groundwater management. In case of mixed facies and heterogeneous alluvium aquifer system, it is difficult to predict the groundwater behavior and its responses to daily usage/withdrawal. Kohat Basin is one of such geological entity where the complex geology has resulted in multifarious groundwater flow pattern. To model the complex groundwater system of the Kohat Basin, a three dimensional numerical flow model using MODFLOW was developed to study the groundwater behavior and design early warning management strategies. From the analysis of results of 10 years model runs, it is noted that groundwater level has been dropped by approximately 30 meters until December 2017. The direction of groundwater flow has been found to be same from northeast and northwest to southeastern part during the entire simulation period. To combat the situation, there is a need to adopt proper strategies to maintain the safe yield. The high pumpage of groundwater in many parts on a long-term basis may result in unsafe decline of groundwater table. The annual extraction of groundwater should not be more than the estimated annual recharge, such as the storage of groundwater must be sufficient to bridge the temporary needs of extraction during dry periods. The developed model could provide an effective tool for evaluating better management options of the Kohat Basin Pakistan for sustainable use of groundwater of the area.

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