Features of groundwater resources assessment on alluvial fans using a regional-scale hydrogeological model (Kaskelen, South Kazakhstan)

Timur Rakhimov, Valentina Salybekova

Kazakh National Technical University named after K.I.Satpayev
Kazakhstan, Almaty

Abstract
Groundwater has provided around 40-60% of the total water supply in South Kazakhstan. The extensive groundwater exploitation has led the Geology Committee to recently rule that the Kaskelen groundwater field is threatened overdraft, i.e., annual pumping rate exceeds annual recharge. Natural recharge consists primarily of mountain-front recharge, river run-off loss and precipitation; therefore, natural recharge plays a major role in further water supply of that region. The exact quantity and distribution of natural recharge was uncertain (last studies held in 1965), in order to better understand the volume of natural recharge and to provide a tool for groundwater management, a regional numerical model was developed. Model was created using Visual MODFLOW and calibrated using WINPEST module with head and drawdown data; prior information was incorporated through the field monitoring data. As a result revealed total water balance, received drawdown due to exploitation, built future scenarios for the deposit exploitation, defined secure pumping flow-rate for the study area. Revealed under the intensive urbanization due to exploitation distributes large depression cone around the city and its surroundings, as a rule, from the center to the periphery. Contemporary water intake system of Kaskelen deposit forms extensive drawdown with a focus on the most intensive site of the urban area, by the way local cones from single water intakes even more complicates exploitation. In areas with severe hydro-geological and hydro-chemical conditions such tendency resulting in irreversible changes in groundwater quality and quantity. All this requires a limitation of water consumption in urban areas against the wishes of the individual subsoil users, as well as conduction effective monitoring on groundwater quality change. The results of this work could be considered as a tool for the future water-management regulations, as a basis for development of a real-time model for groundwater level and water intake monitoring system. This research work and methodology are replicable and could be applied to other groundwater deposits formed on alluvial fans or other under similar conditions.

Keywords: GROUNDWATER MODELING, DRAWDOWN, GROUNDWATER FLOW, GROUNDWATER RECHARGE

Introduction

Territory of Kazakhstan is located in the arid zone facing with the problem of water supply with fresh drinking water (UNDP Reports 2003, 2004, 2006; Aquastat, 2015). One of the ways for solving them is in increasing use of groundwater resources. GIS technologies and mathematical modelling are the main methods for groundwater study, research, evaluation and monitoring nowadays. Development of techniques adapted to geological and hydrogeological conditions in Kazakhstan, as well as scientific methods for efficient monitoring and management using hydro-geological modelling is the actual subject of the research.

Prior to 1991, groundwater had provided less than 30% of the overall water supply in Kaskelen, South Kazakhstan (Fig. 1), but the situation changed since the Kaskelen city was agglomerated to Almaty with a population growth from 14,000 people in 1966 to 64, 200 people in 2014 (Kaskelen, 2015). During this time, groundwater extraction was primarily used for drinking water supply and agricultural purposes and reached a peak of approximately 17 000 m^3/day in 2009 (Yasinsky V.A. et al, 2010). Since 1991, urban groundwater supply has increased significantly and agricultural water supply declined. By 2014, groundwater extraction resulted level drawdown of more than 20m and land subsidence of about 0.5-0.8m in some areas of the basin. Tendency for population growth as well as water demand still increase.

The objectives of this study are to make an assessment of groundwater reserves, estimate groundwater balance and to define so-called "safe yield" for future exploitation of the deposit. For these purposes groundwater-flow and balance mo-del was created and calibrated (Salybekova V. et al. 2014). Model was calibrated with embedded in PEST Gauss-Marquardt-Levenberg algorithm (Gavin H.P., 2013; Siade 2015). As a result three-layer model resulted in an estimate of total natural recharge of 8.06 m^3/sec and provided recommended "safe yeild" of 1.43 m^3/sec.

Study area

Kaskelen groundwater field is a deposit formed on alluvial fan sediments, about 20 km to the west of Almaty, Kazakhstan (Fig. 1). Generally, Kaskelen groundwater field has clearly defined geological and hydrogeological boundaries. On the south, there is a boundary along the contact of Quaternary boulder-pebble deposits of alluvial fan with deposits of Fluvioglacial Lower Quaternary foothill stage. Eastern boundary of the deposit revealed along the contour of Middle Quaternary sediments, forming the area between Aksai – Kaskelen river basins, as well as a series of loamy outcrops of Lower Quaternary sediments. Western boundary of the field coincides with the contour of Lower Quaternary sediments, composed of loams and forming a ridge to the north-east. Total thickness of aqueous sediments within the alluvial fan according to geophysical data is around 500 m or more (Shestakov V. et al., 1965). Administratively, Kaskelen groundwater field distributed to the Karasai district of Almaty region. Large settlements of the district are: Kaskelen city, Ushkonyr, Zhambyl, Ulan and other villages. Land use in the area is mainly urban and agricultural. Climate in the area is arid.

Figure 1. Map showing the location of Kaskelen groundwater field study area, South Kazakhstan

Hydrogeology

Kaskelen groundwater field located in the south-western part of Ili depression formed in era of Alpine orogeny as a result of repeatedly block tectonic movements. Due to the constant tendency to lowering following area formed as accumulative complex of terrigenous sediments. The occurrence of alluvial fans in the foothills of Zaili Alatau is a natural process of region geological development and reflection of their structural position. Main part of the field takes Kaskelen and Chemolgan alluvial fans with an area of 88, 0 sq. km., and the foothills with an area of 178.4 sq. km. Total field area is 266,4 sq. km. Fan sediments characterized by homogeneous lithological compound. Aquifers have close hydraulic connection. Therefore, these alluvial fans are treated as a single entity. Its length from the south to the north (from the ridge to the zone of groundwater seepage) reaches 8 km. Overall width in the billing section reaches 13.5 km.

Hydrogeological conditions of Kaskelen field are defined by its geology, tectonics, and lithological composition of rocks, geomorphological and climatic conditions of the area. Alatau mountain peaks are groundwater recharge area, where precipitation and runoff from mountain rivers further transform and filter to groundwater. General groundwater flow direction goes from mountains toward to the river valley (to the North).

Kaskelen field, like other fields in the foothills, proved extremely favorable conditions for the accumulation of groundwater such as:

- Significant thickness of alluvial sediments;
- High permeability of the sediments;
- Presence of a significant surface flow;
- Relatively large amount of precipitation.

There are several water-bearing complexes revealed on alluvial cone perspective for groundwater supply of the region (Fig.1, Fig.2):

Upper-Quaternary-Modern alluvial aquifer (aQ_{IV} ***)*** spill out along the modern river valleys, within the 1st and 2nd terraces of floodplain, as well as on the zone of temporary streams. Aquifer composed of boulder-pebble and gravel formations, replaced with the distance from the mountains with gravel-pebble, sands interlaying with sandy loams and loams. Horizon occurs at depths 0.5-7.0 m. Aquifer thickness varies from 10-15m. According to the experimental pumping borehole production is equal to 0.1-1.5 l/sec. Groundwater salinity varies from 0.5-1.6 g/l. Aquifer recharge occurs mainly due to the loss of surface runoff and overflow from lower aquifers and complexes.

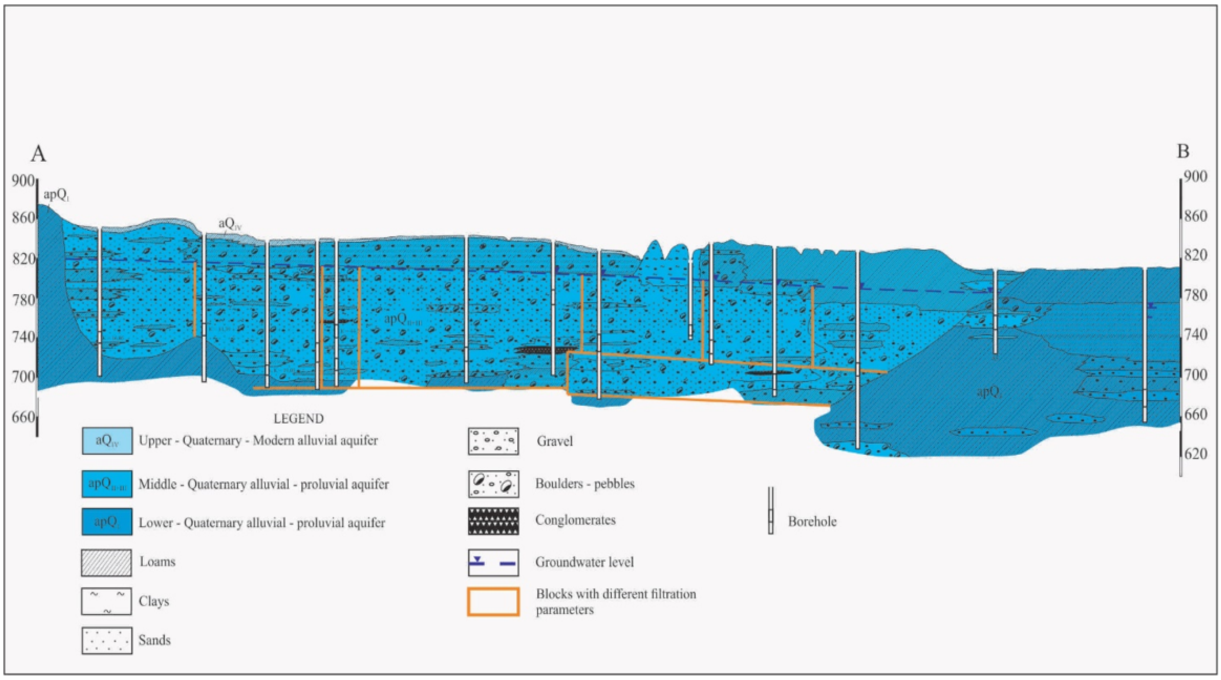

Figure 2. Schematical hydrogeological cross-section on Kaskelen groundwater deposit

Upper-Quaternary alluvial-proluvial aquifer (apQ_{II-III} ***)*** circulated within the Kaskelen and Chemolgan alluvial fans. Composed of permeable coarse clastic sediments, which are adjacent to the intrusive rocks and Paleozoic mountain frame, that creates favorable conditions for the overflow of water fractured rock structures, filtration of surface water and infiltration of precipitation. In the north there is a reduction in power clastic sediments, some deterioration of filtration properties. Actually received specific flow rates range from 8.0 to 17.9 l/s. Groundwater salinity is equal to 0.2-0.5 g/l.

Middle-Quaternary alluvial-proluvial aquifer (apQ$_{II}$) is widely spread within the piedmont plains of Kaskelen, Aksai, Chemolgan Rivers. Aquifer contains pressure hydraulically related to apQ$_{II-III}$ groundwater reserves. Confined aquifer lies on a depth of 13.7 to 150-180 m. Boreholes production rate is in the range of 4,3-40,0 l/s on a level of 2,2-15,6 m.

Lower-Quaternary alluvial-proluvial aquifer (apQ$_{I}$) distributed in the lower section of the fan, and lies on the eroded surface of the Pliocene sediments. Outcrops of Lower-Quaternary sediments forms hills on the piedmont plain. Lithological compound of the water-bearing layers varies from boulder – pebbles and pebbles within the alluvial fan to the sandy loams and fine-grained sands, gravels and conglomerates with interlayers of loams, sandy loams and clays in the piedmont plain. Groundwater salinity is up to 0.15-0.5 g / l. Average borehole rates are 25 - 50.0 l/s.

Groundwater model

The developed three-layer model was used to estimate allowable groundwater abstraction for safe exploitation of the deposit. Model was created in Visual MODFLOW using an upstream weighted finite-difference method (VM Tutorial, 2014; VM User's Manual 2006) resulting in greater stability when simulating complex nonlinear systems, especially systems containing model cells that transition from dry to wet or vice versa (Hill M.C., 1992;Yang Q.C. et al, 2011). This is particularly important for this study as most of the natural recharge occurs along the mountain boundaries where the basin fill is relatively thin and the model often contains only one active layer. In these conditions, model is quite sensitive to having cells become dry or inactive during the calibration or run, which can lead to instability of associated parameter estimation (Hoffman J., 2003; Zhou Y. et al, 2011).

Model discretization

Hydrogeologic conceptualization developed using stratigraphic, hydrologic and water-quality data. Hydrogeological conditions in the plan schematized as a filtration zone 41 x 56.3 km and total area of 2,308.3sq. km. Model outer boundaries assume natural and hydrogeological conditions. Simulated area is approximated as orthogonal grid size M x N = 100 x 200m. (Fig. 3)

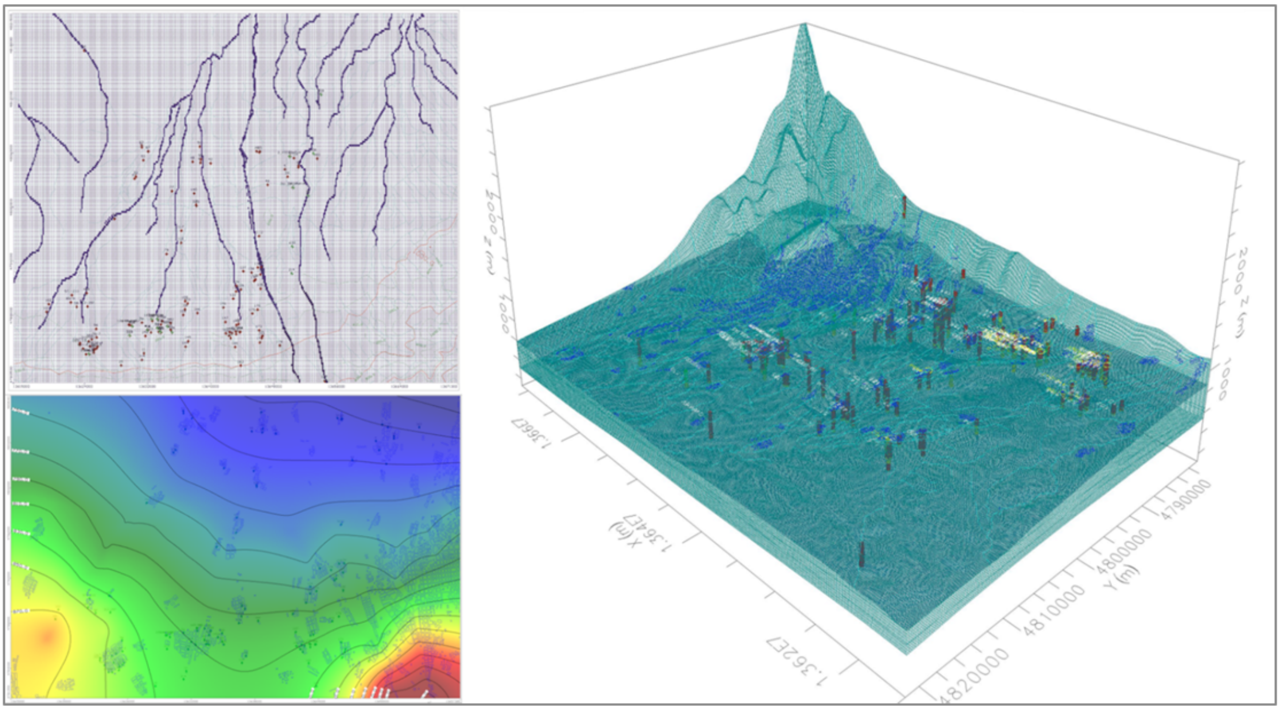

Figure 3. Groundwater model geometry, horizontal discretization, flow boundaries and active cells for Kaskelen groundwater deposit, Kazakhstan

Hydro-geological conditions in a cross-section taken according to the analysis of geological and hydrogeological data, lithology according to geophysical surveys, main hydrogeological properties according to the field surveys. Totally allocated two hydrodynamic floors and created 3 layers:

Layer 1 – Middle Quaternary alluvial-proluvial aquifer (apQ $_{II-III}$);

Layer 2 - Interlayer of dense loams (aquitard layer);

Layer 3 – Lower - Quaternary aquifer (apQ_I);

Natural conditions and pumping were simulated using specified flux boundary conditions, and all other groundwater discharge was simulated using head-dependent boundary conditions. Head-dependent flux boundaries were used in the form of general-head boundary (GHB package), ET (EVT package) and river (RIV package) boundaries to simulate groundwater flowing into and out of the model domain (Lerner D.N., 2002; Harbaugh 2005). Specified-flux boundaries were used in the form of multi-node wells (Halford and Hanson 2002).The MNW1 package was used to simulate groundwater pumping. The MNW1 package internally calculates the vertical distribution of pumpage for wells that are set up through multiple model layers. Outer boundary conditions for the modeling area defined as second order boundaries (ΔQ=const=0). Internal boundary conditions defined as second order boundary (H = const) for Chemolgan, Kaskelen, Aksai, Bolshaya Almatinka and Malaya Almatinka rivers. Single water intakes considered as time-varying flow rate function [Q = f (t)]. Boreholes flow rate for the period of exploitation considered as real data from groundwater monitoring during exploitation.

Balance equation for the field is defined as follows:

$$Q_{riv.} + Q_{prec.} + Q_{bound.} = Q_{evap.} + Q_{expl.} + Q_{trans.} + Q_{out.} \quad (1),$$

where, $Q_{riv.}$ – Infiltration from river flow;

$Q_{prec.}$ – Infiltration from precipitation;

$Q_{bound.}$ – Groundwater inflow from external boundaries;

$Q_{evap.}$ – Total evaporation;

$Q_{expl.}$ – Groundwater exploitation volume;

$Q_{trans.}$ – Evapotranspiration;

$Q_{out.}$ – Groundwater outflow;

Compliance of formed hydrodynamic model to natural conditions proved by model stationary solution (model calibration), performed with the aim of:

- Clarification of certain hydrogeological parameters and boundary conditions;
- Estimation natural elastic reserves and groundwater balance;
- Determining the value of groundwater balance components and their distribution on the area;
- Revealing initial conditions for the solution of forecasting problems.

The first criterion for model adequacy to natural conditions is a coincidence or a close match of obtained levels on the model to the real natural surface level as well as feasible water balance estimations and its distribution within area. Comparison of model and natural conditions was estimated by the data on 18 parametric boreholes (Fig. 4).

Model calibration

The calibration of the hydrogeological model is one of the most important steps during model development. PEST module was used to calibrate the model. PEST is a model-independent estimation postprocessor (Doherty 2010) that using Gauss-Marquardt-Levenberg method (Levenberg 1944; Marquardt 1963) on a nonlinear regression algorithm iteratively updates parameter values until the sum of the objective function is minimized as possible. Uncertainty rate by the results of groundwater modeling calibration for stationary mode (*Mean Error, Mean Abs. Error, and Root Mean Sq. Error)* defined as follows:

Mean Error :

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_c - h_0)_i \quad (2)$$

where, п- number of observation boreholes, h_c и h_0 - calculated and measured groundwater level.

Mean Absolute Error :

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(|h_c - h_0|)_i \quad (3)$$

Root Mean Sq. Error :

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_c - h_0)_i^2} \quad (4)$$

The comparisons between observations and their corresponding model-simulated equivalents for steady-state flow displayed in Figure 4.

By the results of steady-state flow solution the following conclusions were made:

1. Data analysis by the results of groundwater calibration shows high model convergence to natural conditions. Groundwater balance by the results of stationary mode run is shown in Fig. 5.
2. Total groundwater inflow is equal to 8.06 m^3/s. Around (52%) of their formation is due to river flow loss, around 35% due to groundwater inflow from external boundaries and 13% on precipitation.
3. Groundwater discharge is mainly formed by groundwater outflow (around 60%) and river leakage (around 40%).
4. By the results of steady-state solution we can make a conclusion that the model is adequate to natural conditions. The results were taken as the initial for the next phase of calculations.

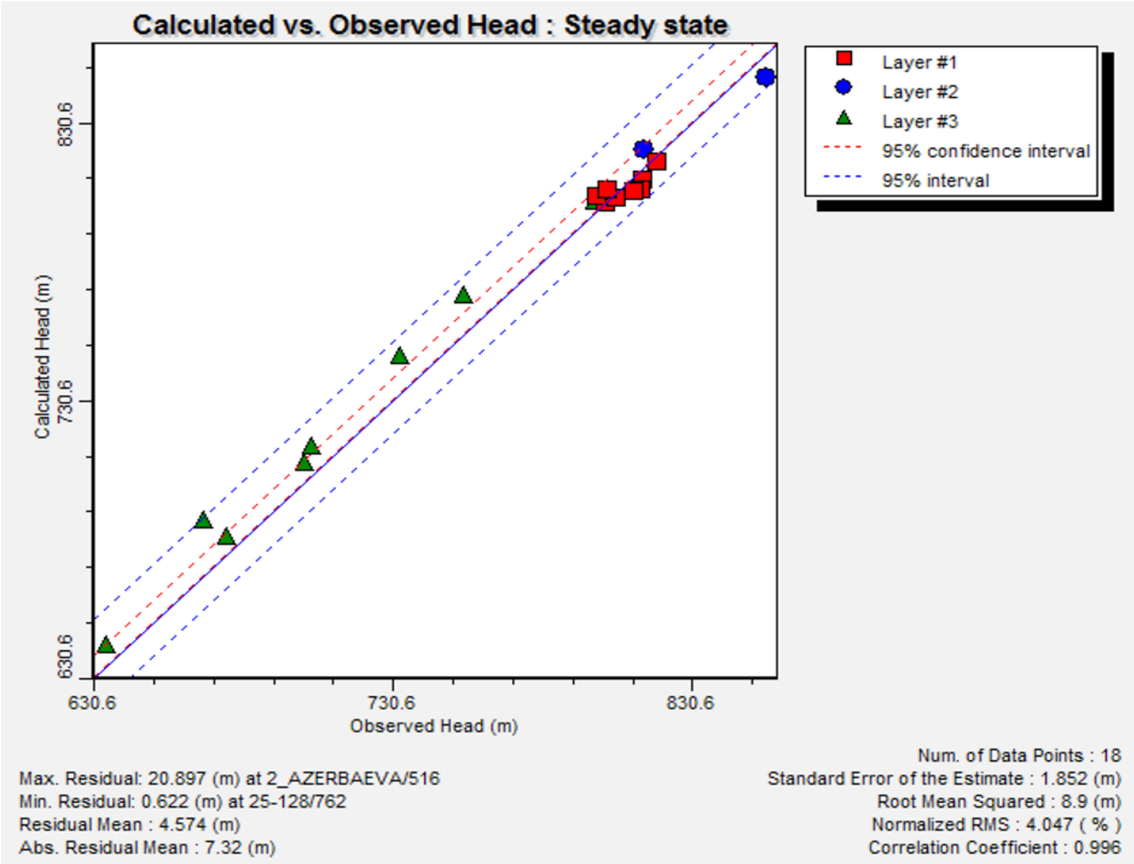

Figure 4. Mean square error according to the stationary mode (steady state flow)

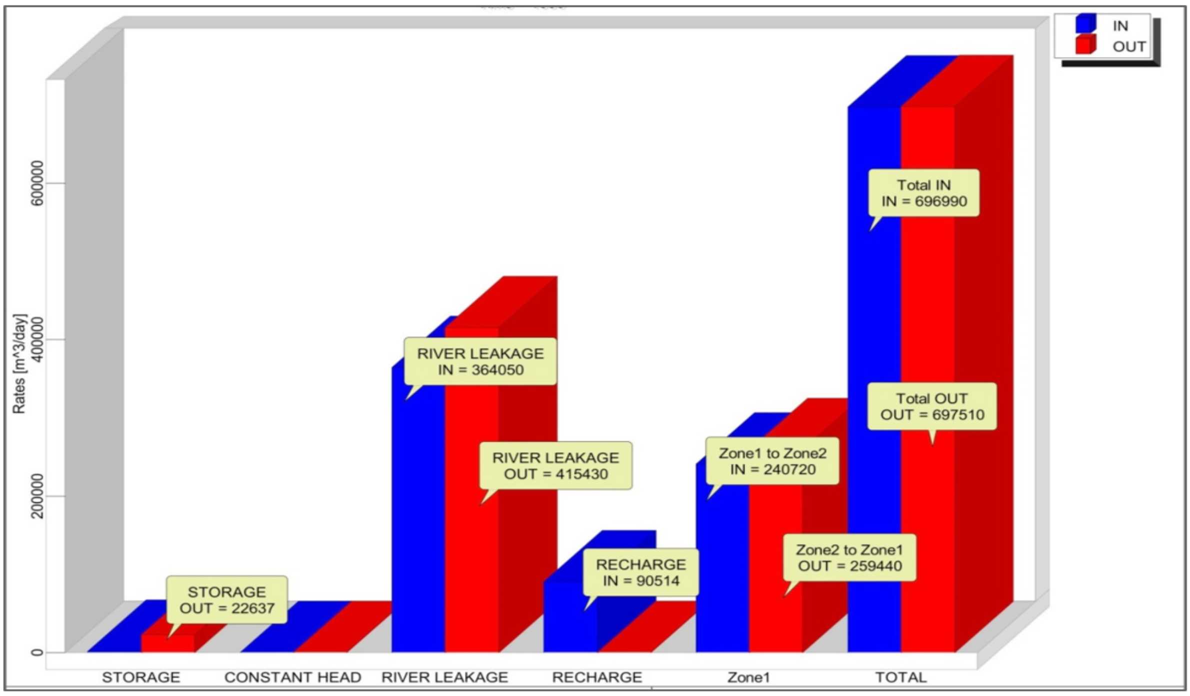

Figure 5. Model balance elements

Calibrated model simulation results

To estimate forecast groundwater level, give predictions for the next period of deposit exploitation and compare it with acceptable values there were defined the following values:

- prognostic boreholes flowrate;
- groundwater levels in all boreholes and wells;
- defined level of influence on the environment due to the groundwater intake;
- assumed influence of Yzunagash, Karoi, Boroldai and Almaty groundwater fields;

Simulated hydraulic head isolines for model layer 3 (basic aquifer for groundwater extraction) shows good compilation with both field level data and total simulated drawdown at the end of the simulation period (Figs. 6 , 7). Overall, the model reproduces historical observations with a reasonable level of accuracy.

The most noticeable impact due to the abstraction is shown on the central intake in Kaskelen. The results of modeling showed that perspective "safe yield" equaled 124200 m^3/day will not cause level drawdown higher than allowable values. About 410,03 GL of cumulative groundwater pumpage was abstracted during the exploitation period (transient-flow run) of 1966–2013. The decline in hydraulic head (Fig. 6) is the result of this depletion in groundwater storage of the deposit. The model developed in this study can be used to help evaluate water-management scenarios throughout Kaskelen groundwater field. River leakage and mountain-front recharge is assumed to be the primary source of natural recharge. The numerical solution procedure known as the WHS Solver in Visual MODFLOW has been employed. This solver's enhanced capability improves the overall numerical stability of MODFLOW with particular improvements in simulating model cells that transition from wet to dry and vice versa. The hydrogeological model was calibrated using the parameter estimation and predictive-uncertainty postprocessor PEST. All model parameters were defined such that they tend toward expected parameter values, based on professional judgment, geological and hydrogeological surveys of the area. Average annual natural recharge estimated by study results is about 254,40 GL/year, which is very close to the previous estimations and was considered as the prediction of the model.

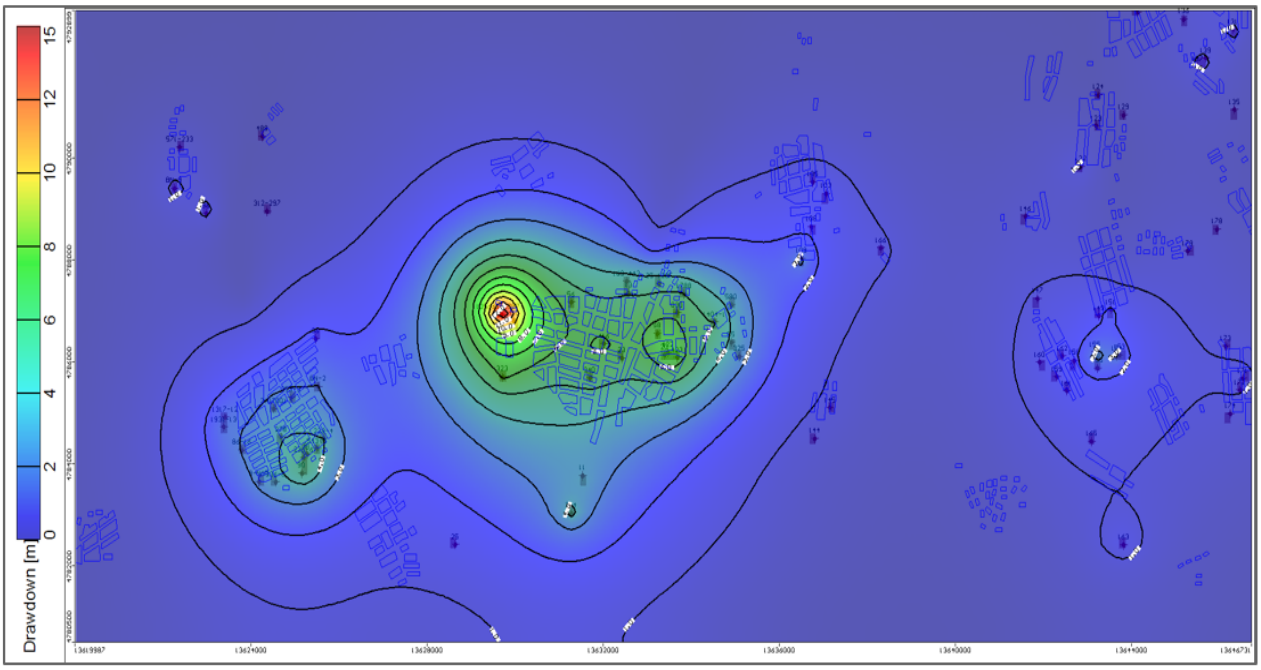

Figure 6. Drawdown by the results of transient flow model run for Kaskelen groundwater field

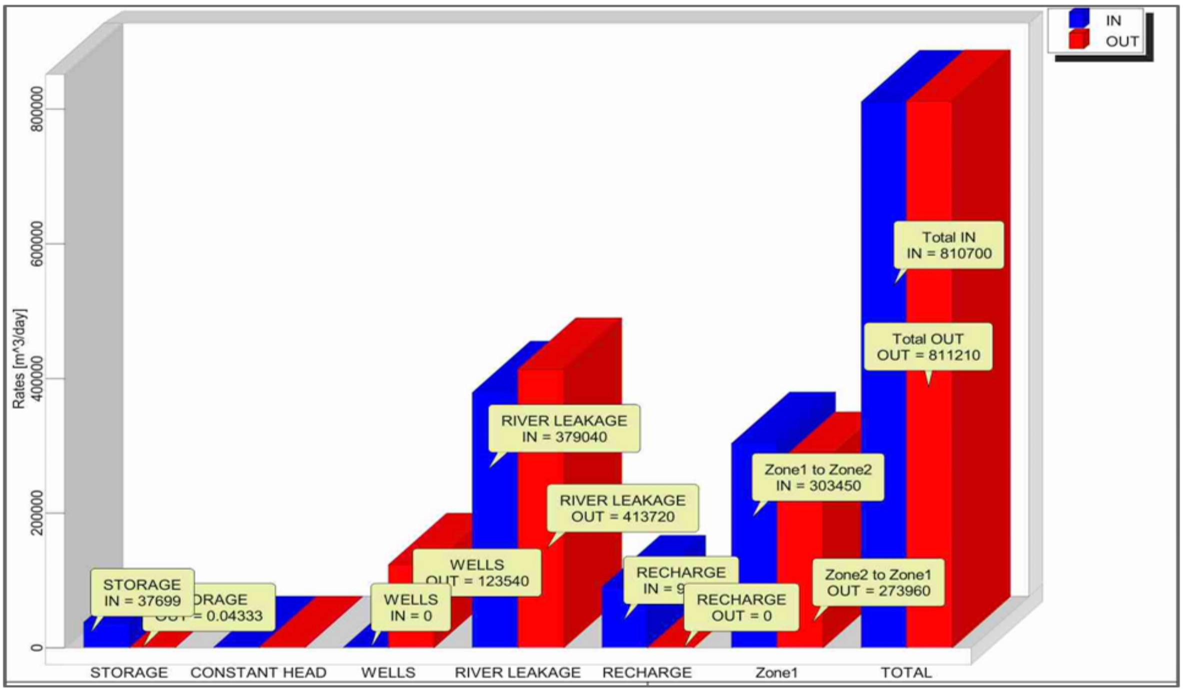

Figure 7. Balance elements by the results of transient flow run for Kaskelen groundwater field

Results and discussion

The results from numerical modeling indicate that the general direction of groundwater flow in Kaskelen is down gradient from areas of Alatau Mountains to the lowland valleys of Kaskelen, Chemolgan and Aksai Rivers. Groundwater levels in the modeled Middle-Quaternary alluvial-proluvial Aquifer are strongly influenced by the rivers and its major tributaries leakage. Agreement between calculated and observed heads is generally within 2–5 m or less than 5 % of the total range in groundwater level across the study area. The model indicates groundwater moves down gradient within the valley hydrogeological units and also shows significant interaction with the surface waters, calculated results confirm estimations from previous works. Kaskelen groundwater model preparation included analysis of hydrogeological conditions, research area conceptual model preparation and input data collection with transformation of consistent units for geo-information technology processing, modeling, calibration and verification of natural physical conditions. Conceptual groundwater model provides an opportunity to simulate possible future scenarios and investigate particular urban development issues in Kaskelen. For example, the numerical model allows the study of the impact of proposed engineering structures on the groundwater levels and flows.

Experience of working on the territories of large cities allows us to formulate main features of groundwater assessment in these conditions.

1. Previous estimations on groundwater demand usually seriously overestimated then the real pumping rate therefore calculations lead to erroneous calculated and natural groundwater levels due to the difference of prognostic and real water intake.

2. Flow rate monitoring suggests that water demand exceeds real water intake

3. Under the intensive urbanization due to exploitation distributes large depression cone around the city and its surroundings, as a rule, from the center to the periphery. As a result of such system forms extensive depression with a focus on the most intensive site of the urban area

4. There is a tendency of subsoil user growth, forming local cones from single water intakes that complicate exploitation.

5. In areas with severe hydrochemical zoning such tendency resulting in irreversible changes in groundwater quality. All this requires a limitation of water consumption in urban areas against the wishes of the individual subsoil users, as well as thorough monitoring on groundwater quality change.

Experience of work performed shows that long-term monitoring of groundwater levels as well as water consumption and groundwater quality, coupled with computer modeling allows us to set main trends of their changes and predict future drawdown, in short and medium terms. The results of this work can provide a basis for real-time mathematical models, as an integral part of the direct monitoring.

Acknowledgements

This work was supported by Committee of Geology of the Republic of Kazakhstan and Kazakh National Technical University named after K.I.Satpayev. Publication and study grant funded by Ministry of Education and Science of the Republic of Kazakhstan. A special thanks to Professor Zavaley and Professor Kalitov, Kazakh National Technical University (Kazakhstan) and to Professor Tomas Saks, Latvian University (Latvia) for the support and valuable consultations.

References

1. AQUASTAT Survey, (2012). Irrigation in Central Asia in figures. Available at: http://www.fao.org/nr/water/aquastat/countries_regions/kaz/KAZ-CP_eng.pdf
2. Doherty J (2003) Groundwater model calibration using pilot points and regularization. Ground Water 41(2):170–177. doi:10.1111/j.17456584.2003.tb02580.x
3. Doherty J (2010) PEST, Model-independent parameter estimation: user manual, 5th edn. (and addendum to the PEST manual).Watermark, Brisbane, Australia. Available at: www.pesthomepage.org. June 2015
4. Doherty JE, Fienen MN, Hunt RJ (2010) Approaches to highly parameterized inversion: pilot-point theory, guidelines, and research directions. US Geol Surv Sci Invest Rep 2010–5168,36 p.p.
5. Doherty, J.E., Fienen, M.N., and Hunt, R.J., 2010, Approaches to highly parameterized inversion: Pilot-point theory, guidelines, and research directions: U.S. Geological Survey Scientific Investigations Report 2010–5168, 36 p.
6. Gavin H. P., 2013. The Levenberg-Marquardt method for nonlinear least squares curve-fitting problems. Available at: http://people.duke.edu/~hpgavin/ce281/lm.pdf
7. Halford KJ, Hanson RT (2002) User guide for the drawdown-limited, multi-node well (MNW) package for the U.S. Geological Survey's modular three-dimensional finite-difference groundwater flow model. US Geol Surv Open-File Rep 02-293, 33 p.p.
8. Harbaugh AW (2005) MODFLOW-2005, the U.S. Geological Survey modular groundwater model: the groundwater flow process. US Geol Surv Tech Methods 6-A16
9. Hill, M. C., 1992: A Computer Program (MODFLOWP) for Estimating Parameters of a Transient, Three-Dimensional, Ground-Water Flow Model using Nonlinear Regression. U. S.Geological Survey Open-File Report 91-484.
10. Hoffman J, Leake SA, Galloway DL, Wilson AM (2003) MODFLOW-2000 groundwater model: user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. US Geol Surv Open-File Rep 03-233, 44 p.p.
11. Kaskelen (June 27, 2015) In Wikipedia, the free encyclopedia. Available at: https://ru.wikipedia.org/wiki/%D0%9A%D0%B0%D1%81%D0%BA%D0%B5%D0%BB%D0%B5%D0%BD.
12. Lerner D.N. (2002) Identifying and quantifying urban recharge: a review. Hydrogeol J 10:143–152.
13. Levenberg K. (1944) A method for the solution of certain non-linear problems in least squares. Q J Appl Math 2:164–168.
14. Marquardt DW (1963) An algorithm for least-squares estimation of nonlinear parameters. J Soc Ind Appl Math 11(2):431–441.
15. Salybekova V., Rakhimov T.A., 2014. Report on the results of further assessment of Bakanas, Issyk and Kaskelen groundwater fields in Almaty region. LLP "Geotherm" Production Company", Almaty , Kazakhstan.
16. Shestakov V., Korostova A., 1965. Kaskelen groundwater field assessment report. Almaty hydrogeological party, Almaty, USSR.
17. Siade AJ, Nishikawa T, Rewis DL, Martin P, Phillips SP (2014) Groundwater-flow and land-subsidence model of Antelope Valley, California. US Geol Surv Sci Invest Rep 2014–5166, 154 p.p.
18. UNDP. 2003. Review of water situation in Kazakhstan. Kazakhstan: National Human Development Report. Chapter 3. New York, United Nations Development Programme.
19. UNDP. 2004. Water resources of Kazakhstan in the new millennium. New York, United Nations Development Programme.
20. UNDP. 2006. National integrated water resources management and water efficiency plan project. Available here, accessed on 26/10/2011. New York, United Nations Development Programme.
21. Visual MODFLOW Flex Integrated Conceptual & Numerical Groundwater Modeling. Available at: http://trials.swstechnology.com/software/VMODFlex/2014/VMODFlex_UsersManual.pdf.
22. Visual MODFLOW v.4.2 User's Manual, 2006 from http://tu-freiberg.de/fakult3/geo/hydro/

modflow/VMOD_42_Manual.pdf.
23. Yang Q.C., Liang J., and Yang Z.P., 2011. Numerical Modeling of Groundwater Flow in Daxing (Beijing), China. SciScienceDirect14: 1671-1676.
24. Yasinsky, V.A., Mironenkov, A.P. & Sarsembekov, T.T. 2010. Water resources of transboundary rivers in the regional cooperation between the countries in Central Asia. Almaty, Kazakhstan, Eurasian Development Bank.
25. Zhou Y., and Li W., 2011. A review of regional groundwater flow modeling. Geoscience frontiers 2(2): 205-214.