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ORIGINAL ARTICLE

3-D numerical groundwater flow simulation for geological discontinuities in the Unkheltseg Basin, Mongolia

Yohannes Yihdego · Cara Danis · Andrew Paffard

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Abstract Groundwater models which realistically represent the hydrogeology of a complex system, like the Unkheltseg Basin, are critically important to Mongolia. They have flow on benefits to research, governments, management strategies and commercial development within the country. Limited case studies of calibrated 3-D numerical transient simulations in fault-controlled connection between basins, similar to the Unkheltseg Basin, are available in the public domain and the model presented here aims to address this problem. This basin is uniquely geologically controlled and a key water supply resource for future economic development in the Taikh Valley. Commercial exploration projects have produced the high-quality geological and hydrogeological data gathered, necessary for successful model simulation at a basin-wide scale. Using the "DRAIN Package" and "Fracture-Well Package FW4" in MODFLOW-SURFACT, the spatial discretization necessary to fully represent horizontal and vertical flow direction was achieved to effectively constrain recharge and discharge across the fault barrier. This model is an important tool for establishing a long-term monitoring programme in a fault-controlled basin, which predicts regional impacts, both short and long term.

Keywords Groundwater · 3-D numerical modelling · Geological discontinuity · Mongolia

Y. Yihdego (✉) · C. Danis · A. Paffard
Snowy Mountains Engineering Corporation (SMEC), Sydney, NSW 2060, Australia
e-mail: yohannesyihdego@gmail.com

Introduction

Groundwater resources play a vital role in Mongolia's economy and the industrial and domestic water demand is mainly met from groundwater sources; about 80 % of the total consumption is from groundwater (Hasiniaina et al. 2010). Modelling of groundwater resources in Mongolia, which is also common elsewhere, is challenging, due to limited information, both published and government data, historical reliance on simple analytical assessments and complex geological systems that present limitations to various modelling techniques. For effective groundwater management resource comprehensive and realistic modelling is essential. Over the past few years, many international companies, working on projects requiring groundwater supply (Oyu Tolgi, Energy Resources UHG Coal Mine, Burun Narran Coal Project), have begun presenting 3-D numerical simulations for resource estimation and using these simulations to calculate resource lifespan and extraction limits, something not possible with the current analytical methods used in Mongolia.

Over the last few years, a number of discussion papers have addressed the issue of how models can best serve the process of decision support. Previous studies (e.g. Gupta et al. 2012; Kresic and Mikszweski 2014; Nordstrom 2012; Simmons and Hunt 2012; Voss 2011) have addressed the extent to which the model's parameters should be adjusted to allow it to replicate past system behaviour as a precursor to its being used in management of future system behaviour and how complex (or otherwise) it needs to be when used in this capacity. In this context, a model's purpose is to predict the behaviour of a system under a management regime. Selection of an appropriate level of model complexity is most difficult where predictions required of a model are only partially constrained by historical data (Doherty and Simmons 2013).

Faulted aquifers constitute one of the most complex geological environments for analysis and interpretation of hydraulic test data because of the inherent ability of faults to act not only as high transmissive zones but also as hydraulic barriers (Bense et al. 2013; Bredehoeft 1997; Cello et al. 2000; Evans et al. 1997; Folch and Mas-Pla 2008; Shan et al. 1995). Whilst our interpretation of the faulted aquifer remains linear in nature, parameter estimation by numerical simulation highlighted the presence of hydraulic barriers associated with the faults. These barriers are readily apparent in the constant discharge test data. Fracture zones and faults have long been identified as having significant influence on groundwater flow and transport because of their contribution to altering the effective permeability of the aquifer. For this reason, there have been numerous investigations aimed at describing a wide range of phenomena, over a range of scales, that are associated with fractures and faulting (Allen and Michel 1999; Nordqvist et al. 1992; Yihdego and Becht 2013). The role of groundwater transfers in geological complex terrain is challenging (e.g. Nelson and Mayo 2014; Yihdego and Webb 2014). In faulted aquifers, additional complexities may exist because faults are often observed to act both as conduits (Huntoon and Lundy 1979; Pimentel and Hamza 2014) and as barriers (Ran et al. 2014; Rojstaczer 1987) to flow. Thus, broad generalisations regarding the influence of faults are difficult to make.

The groundwater resource estimation for the basin region was initially based on yields from pumping tests (Battumur 2009), interpreted analytically by the Cooper–Jacob simplification of the this approach (e.g. Freeze and Cherry 1979; Fetter 1994). This estimation indicated that there could be sufficient groundwater to supply mining activities nearby but numerical modelling was required to confirm and assess the impacts. Snowy Mountains Engineering Corporation (SMEC) was commissioned in 2011 to undertake a pre-feasibility level study and in 2012 feasibility level groundwater resource assessment, focusing on the Unkheltseg Basin as a mine water supply source for Bayan Airag Exploration.

The Unkheltseg Basin

The Unkheltseg Basin is located approximately 930 km west of the Mongolian capital Ulaanbaatar, 250 km south of the border with Russia, in Zavkhan province, Erdenekhairkhan Soum in a region characterised by steep mountainous terrains and wide valleys. The region is dominated by reverse faults, striking parallel to the mountain ranges, which have significant vertical displacement, up to 100 m in some areas. This faulted geometry often disconnects groundwater aquifers in alluvial systems and there is often limited or no hydraulic connectivity across the faults. The basin system appears to be fault block dominated, creating a basin with steep sides and a relatively flat base which conceptually looks much like a bath tub (tank reservoir). The discharge from the basin system into the southern Tost Basin is controlled by the permeability and hydraulic conditions of the barrier as groundwater discharge occurs across a geological discontinuity, which is presumed here to be a fault uplifted basement. Therefore, there is no direct hydraulic connection between the basin and the southern Tost Basin and this groundwater storage–discharge relationship cannot be easily handled by simple analytical equations or 1-D or 2-D numerical simulation programmes. The challenge with 3-D numerical simulations is to produce a model which realistically simulates natural conditions. Using the "DRAIN Package" and "Fracture-Well Package FW4" in MODFLOW-SURFACT, the work presented here shows a successful simulation that correlates well with the hydrogeological conditions observed.

The model scenario problem

In watershed models, the subsurface-saturated domain is often represented by a linear, or non-linear, storage–discharge function (e.g. Fiorillo 2011; Kampf and Burges 2007; Rupp et al. 2009; Singh and Woolhiser 2002; Wenping et al. 2011). In some cases, the derivation of the function begins with a physics-based description of saturated flow, but assumptions made thereafter (e.g. constant head gradient or successive steady states) lead to a single-valued storage–discharge function (e.g. TOPMODEL; Beven and Kirkby 1979).These storage–discharge functions are advantageous in that they are computationally very simple but this representation means at the scale of the model element (e.g. subcatchment) there is no explicit distribution information in any spatial dimension (x, y or z) and the model is considered as zero or one dimensional (e.g. Kampf and Burges 2007). Models which discretise the groundwater domain in two or three dimensions and numerically solve the governing partial equation for saturated flow (e.g. Palma and Bentley 2007; Singh and Woolhiser 2002; Vandenbohede et al. 2011) do have the advantage of being spatially explicit. Using a transient saturated flow model gives analytical solutions to linear partial differential equations subjected to time-varying stress, such as recharge or pumping (e.g. Bidwell et al. 2008; Pulido-Velazquez et al. 2005; Wenping et al. 2011). However, these solutions can be limited to a homogenous 1-D representation of an aquifer, which may entail a severe simplification of the system (Rupp et al. 2009).

A model is a scale-down simplified representation of a natural system. Therefore, the developments of a model presuppose the knowledge of the system. The solution to the problem of how to model the "tank–reservoir" Unkheltseg Basin was to utilise 3-D transient and steady-state

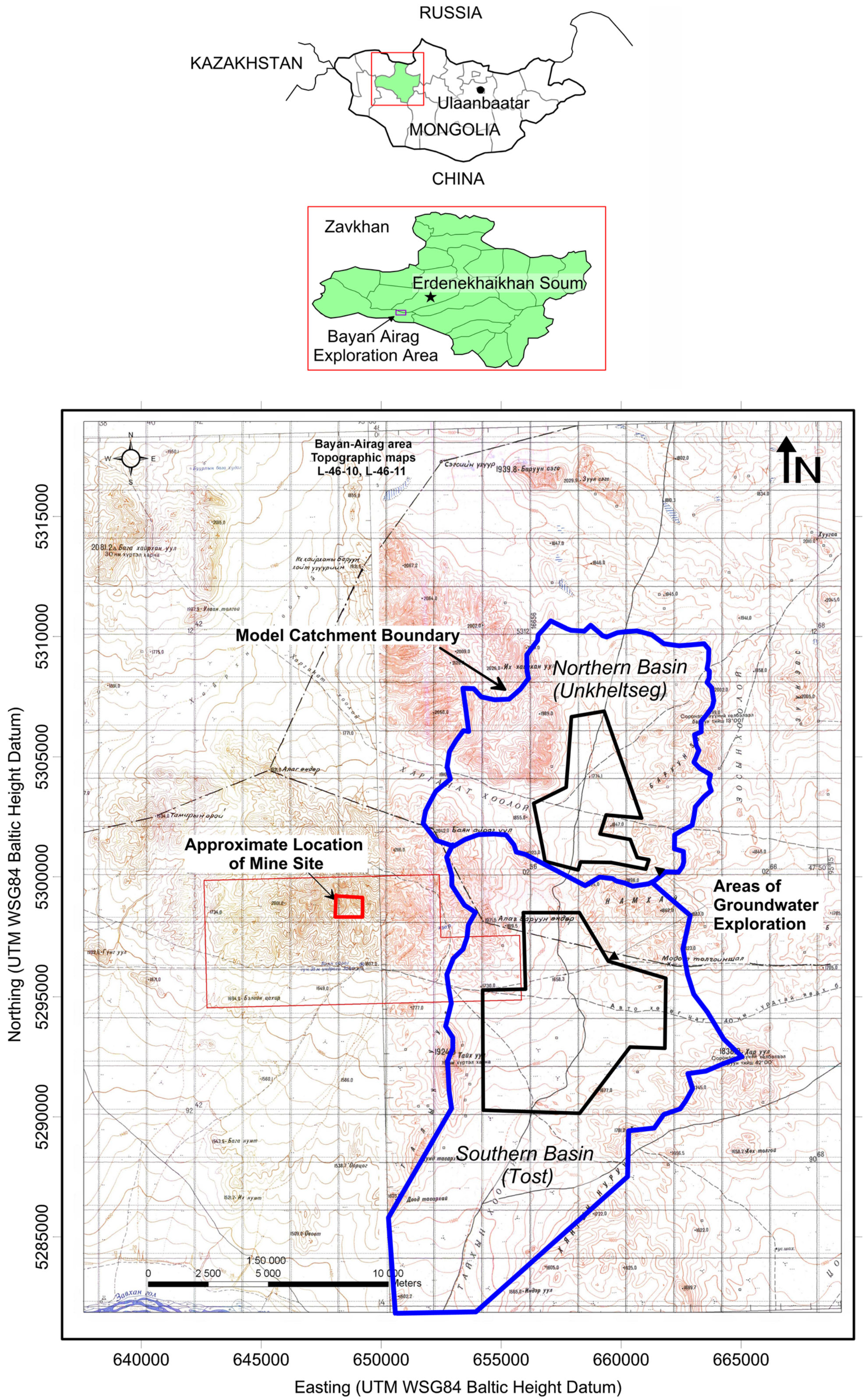

Fig. 1 Location map of the study area

models in MODFLOW-SURFACT, which overcome the drawbacks of the 1-D or 2-D analytical equations, because spatial information (i.e. hydraulic head) is retained in the primary and secondary flow directions and the restrictive assumption that discharge has a one-to-one relationship to aquifer storage is not made (Sloan 2000).

The purpose of this work is to select an appropriate level of model structure and parameterization for the peculiar/unique Unkheltseg basin and to provide a successful example of 3-D groundwater resource modelling at a basin scale to academics, relevant industries and government agencies in Mongolia. A detailed and accurate modelling is critically important to Mongolia, because this basin system is unusual in that recharge is limited, the system is geologically controlled and the system potentially has a maximum groundwater level which when reached allows discharge to the down gradient Tost Basin. Recharge in the Tost Basin is primarily from discharge of the Unkheltseg Basin, an interesting link that poses resource management challenges for the area. The Unkheltseg Basin aquifer system located in the Taikh Valley in northern Mongolia (Fig. 1) was assessed via computer 3-D numerical steady state and transient flow simulations, using MODFLOW-SURFACT, for the groundwater resource potential to supply water for a nearby mine and the potential impacts of extraction.

This paper describes the conceptual model and the numerical approach, and demonstrates the importance of using transient simulations for model calibration. The objective is to demonstrate the effectiveness of transient numerical modelling as an important tool and interpretation of data from complex aquifer regimes, particularly those that are derived from faulted aquifers on the basin scale.

Background and data sources

The purpose of this work is not to reproduce the SMEC report but to summarise relevant information and present the groundwater simulations and results. Most of the information presented in this paper and associated assumptions and interpretations have been sourced from the following consultant's reports: EcoTrade (2007), Battumur (2009), SMEC (2011, 2012) which are confidential at present. Bayan Airag Exploration has provided permission for the work undertaken by SMEC (2012) and associated interpretations to be published in this paper. This work provides one of a few published hydrogeological numerical assessments in Mongolia, benefiting the Mongolian scientific community and providing a reference tool for consultants and academics working on similar basin systems.

SMEC's (2012) study focused on a quantitative assessment of the potential of the aquifer as a water supply source to meet the mining demands using steady and transient numerical groundwater flow models. The average mine water demand is expected to be 9 L/s with a peak of 17 L/s and minimum or 4.2 L/s with a proposed mine life of 7 years (excluding construction). Therefore, the project required water supply of up to (2.82×10^5 m^3/year) 9 L/s for a period of 7 years. In addition, the study assessed the effects of the groundwater development from simulated long-term extraction.

Climate and topology

The climate in the region of the basin is characterised by warm summers and cold winters with temperatures ranging between −38 and 30 °C. Precipitation has been recorded at Dorvuljin Soum some 30 km south of the basin. The average for the past 10 years is 90 mm, of which around 90 % falls during the summer months of June–August. Anecdotal evidence suggests that rainfall on the mountain range west of the basin (comprised of limestone) may be higher due to orographic effects. The area is mountainous with elevations ranging between 1,670 and 2,160 m above sea level with the floor of the basin ranging in elevation from 1,720 to 1,800 m above sea level, with its lowest point in the south. It is surrounded by a limestone mountain to the west and hills to the east. The basin drains south towards the Zavkhan River, approximately 30 km away. The basin has no permanent surface water bodies (i.e. springs, lakes, permanent rivers). Surface flows only occur after intense rainfall events which exceed infiltration rates.

Geology and hydrogeology

The basin is infilled with quaternary unconsolidated sediments overlying a Riphean aged bedrock basement comprising limestone (west and north west), tonalite, quartz, diorite and granite (east and south) (Fig. 2). Two main aquifer types were identified: the unconfined to semi-confined dilluvial/colluvial unconsolidated sediments and confined bedrock Riphean Shuvuun Formation (Ecotrade 2007). The unconsolidated aquifers are distributed near the slopes of mountains and through the ravines and dry river beds and consist of gravel and pebbles, small clay lenses and small boulders. Pre-feasibility reports and hydrogeological assessments have characterised an upper and lower aquifer separated by a leakey, low permeability, aquitard (SMEC 2011). The Shuvuun Formation is a low yielding bedrock aquifer with limited interconnection and extent (Battumur 2009).

Table 1 summarises the results of testing of bores in the Unkheltseg Basin (Unkheltseg Bore) and south of the basin (Tost and Oortsog Bores). The information suggests that the Unkheltseg Bore was pumped for 72 h with 2 m drawdown and reached full recovery after 2 h. Groundwater quality is dominated by sodium and magnesium cations and chloride, sulphite and carbonate anions. Salinity varies between 800 and 1,800 mg/L. None of the samples have a 'typical' signature expected from a

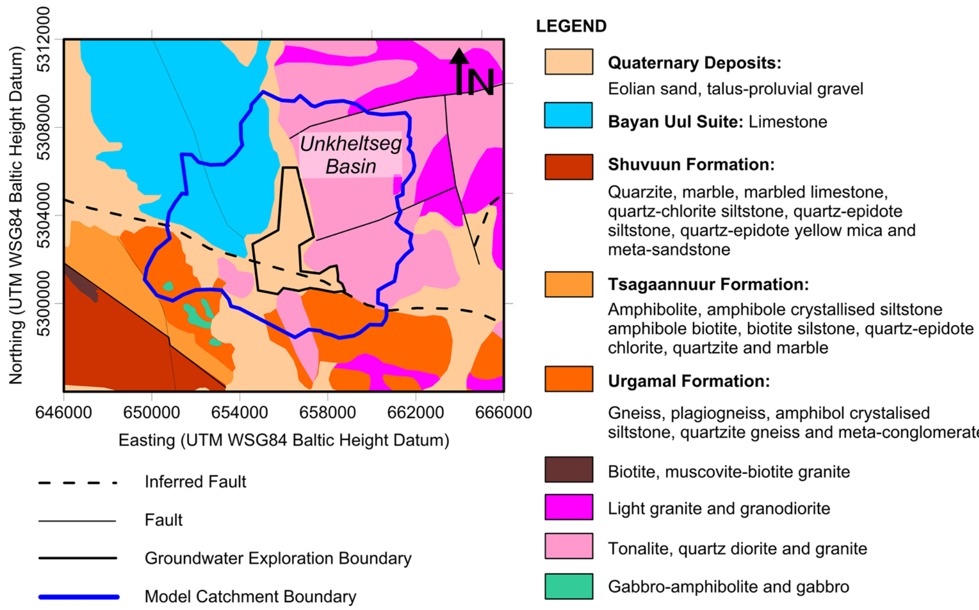

Fig. 2 Geological map of the study area

Table 1 Summary table of existing bores in quaternary aquifers located within or close to the targeted basins (source: Battumur 2009)

Name of drilled well	Depth of well (m)	Static water level (mbgl)	Well yield (L/s)	Water level drawdown (m)	Nature of rock of water-bearing strata
Oortsog	60.0	13.0	0.83	33.0	Lower–middle quaternary proluvial sediments ($Qi_{i–iii}$)
Unkheltseg	51.0	29.0	4.0	2.0	Lower–middle quaternary proluvial sediments ($Qi_{i–iii}$)
Tost	117.0	68.0	2.7	–	Lower–middle quaternary proluvial sediments ($Qi_{i–iii}$)

carbonate aquifer. There is a lot of carbonaceous rocks in the area, but the water does not show a lot of significant interaction with this rock type. The water quality is generally good with low salinity suggesting reasonable recharge and short residence times.

Battumur (2009) also describes the Riphean Shuvuun Formation Aquifer which contains the Bayan Airag Deposit. Five vertical bores were drilled, of which two were dry and three intersected water. The results of airlift testing are summarised in Table 2.

Downhole geophysical logging was undertaken in four boreholes to identify the interbedded silt/clayey and gravel layers. The methods used were: natural gamma (Gamma) (GP), density (Gamma Gamma), calliper, single-point resistance (PR), and spontaneous potential (SP), conductivity. An induced polarisation (IP) survey was conducted by GeoMaster Engineering LLC. Five lines totalling 24,000 m were surveyed using a 100-m dipole spacing. The data were calibrated by QGX Mongolia LLC against the existing drilled boreholes to provide a depth to basement along the line. This was then used by QGX to contour the basement profile.

The Unkheltseg Basin is interpreted to be a block-faulted basin in filled by transported sediments. The sediments are unconsolidated to weakly indurated and likely represent several phases and types of deposition including:

- dilluvial glacial outwash deposits;
- aeolian sand dunes;
- elluvial/colluvial deposits shed from the surrounding hills into the basin;
- alluvial wash during floods; and
- low-energy shallow lake deposits during wet periods or developed at the deepest part(s) of the basin.

Lithological layers are not continuous across the entire basin. In particular, clay or sandy clay layers are discontinuous and may represent ephemeral lakes which formed in the deepest parts of the basin and likely moved around depending on climate and on-going subsidence. Cross-sectional locations and inferred faults are provided in Figs. 3a and 2, respectively. The cross sections and interpreted units are provided in Fig. 3b. From the induced

Table 2 Airlift test results for mine area bores

Borehole number	Yield (L/s)	Drawdown (m)	Thickness of water-bearing zone (m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)
CVZDH 122	1.1	51	31.4	0.38	11.93
CVZDH 124	0.027	42.6	28.5	0.0092	0.26
CVZDH 125	1.2	37.7	57.5	0.0857	4.93
Arithmetic average value			36.33	0.16	5.71

Source: Battumur (2009). See Fig. 1 for the location of mine site

polarisation survey, drilling results and cross sections, it is clear the Unkheltseg Basin is enclosed and can be thought of as a '*tub full of water and sediment*'. The Unkheltseg basin is interpreted to be an infilled block-faulted basin and as such the lithological layers are not continuous across the entire basin. The groundwater gradient, at 0.0015, is very flat and only increases slightly in the northern part to around 0.008 and is likely a response to the basin architecture and recharge and discharge zones. The architecture of the basin is not that dissimilar to a tub in that the basin has steep sides with a flat gently dipping base determined through a drilling exploration programme and geophysical surveying (SMEC 2012). The very flat groundwater gradient indicates either high permeability, at least within the upper aquifer, or low recharge.

Water level drawdown responses were observed in the monitored bores and show that:

- the drawdown in the pumping bore is much greater than the nearby monitoring bores suggesting poor bore development;
- the impacts of pumping are transmitted quickly through the upper aquifer and more slowly through the lower aquifer;
- the water level in the upper aquifer declines quickly then continues to decline as a rate much slower than the pumping bore and lower aquifer; and
- the water level in the lower aquifer has a delayed response to pumping and the water level mimics the response in the pumping bore. This indicates reasonable development of the lower aquifer screens.

Water level monitoring indicates that there is no pressure difference between the upper water table aquifer and lower aquifer. This indicates the two are interconnected. The upper aquifer is considered to be semi-confined and the lower aquifer leaky confined. Recovery and pumping test data indicate that the upper aquifer is several times more permeable (on average) than the lower aquifer. Monitoring of water levels conducted since 2010 indicates very little change in the water level over time suggesting either limited recharge during this period or the basin has a spill point which controls the maximum groundwater elevation. The increase in groundwater elevation to the north reflects the decreasing permeability and likely recharge.

Groundwater recharge within the basin predominately results from precipitation via direct infiltration and mountain slope runoff from the surrounding hills and mountains. This occurs mainly through surface runoff which flows from the higher elevated mountains to the basin margins where it infiltrates. Recharge may also occur via lateral and vertical movement from bedrock exposed at surface and this then recharges the basin sediments via fractures/structures from the bedrock below the surface of the sediments. Moreover, recharge may occur from direct infiltration of precipitation which falls on the colluvial basin sediments or from overland flow; this is thought to only occur during very heavy rainfall events. Due to orographic effects, precipitation is considered higher in the mountains surrounding the basins. This suggests that most recharge occurs via mountain front infiltration and bedrock transfer. The low salinity of the groundwater suggests a short residence time and moderate turn over. Recharge is therefore thought to occur directly via mountain front or direct infiltration with low evaporation losses and the groundwater travel distance is short.

The depth to the water table is 36 m at the southern end and over 100 m at the northern end of the basin, too deep for evapotranspiration losses via capillary forces or transpiration via plants. Groundwater discharge from the basin sediments is assumed to occur via base flow through the fault barrier between the basin and the Southern Tost Basin, due to the significant groundwater level changes. No permanent or ephemeral surface water bodies (such as springs, lakes and rivers) are located within the basin. Given the stable groundwater elevations and gradient, based on 18 months monitoring, discharge to the southern basin is assumed to occur when the groundwater level in the basin sediments is at the level indicated by monitoring. Discharge from the Tost Basin eventually reaches the Zavkhan River, which is located 30 km south, which is considered the main groundwater recipient. Minor discharge occurs via abstraction of groundwater for stock and domestic use by the local population.

Water level monitoring (SMEC 2012) indicated that there is no difference between the upper and lower aquifer groundwater levels and suggests that the two aquifers are interconnected. Recovery and pumping test data (SMEC

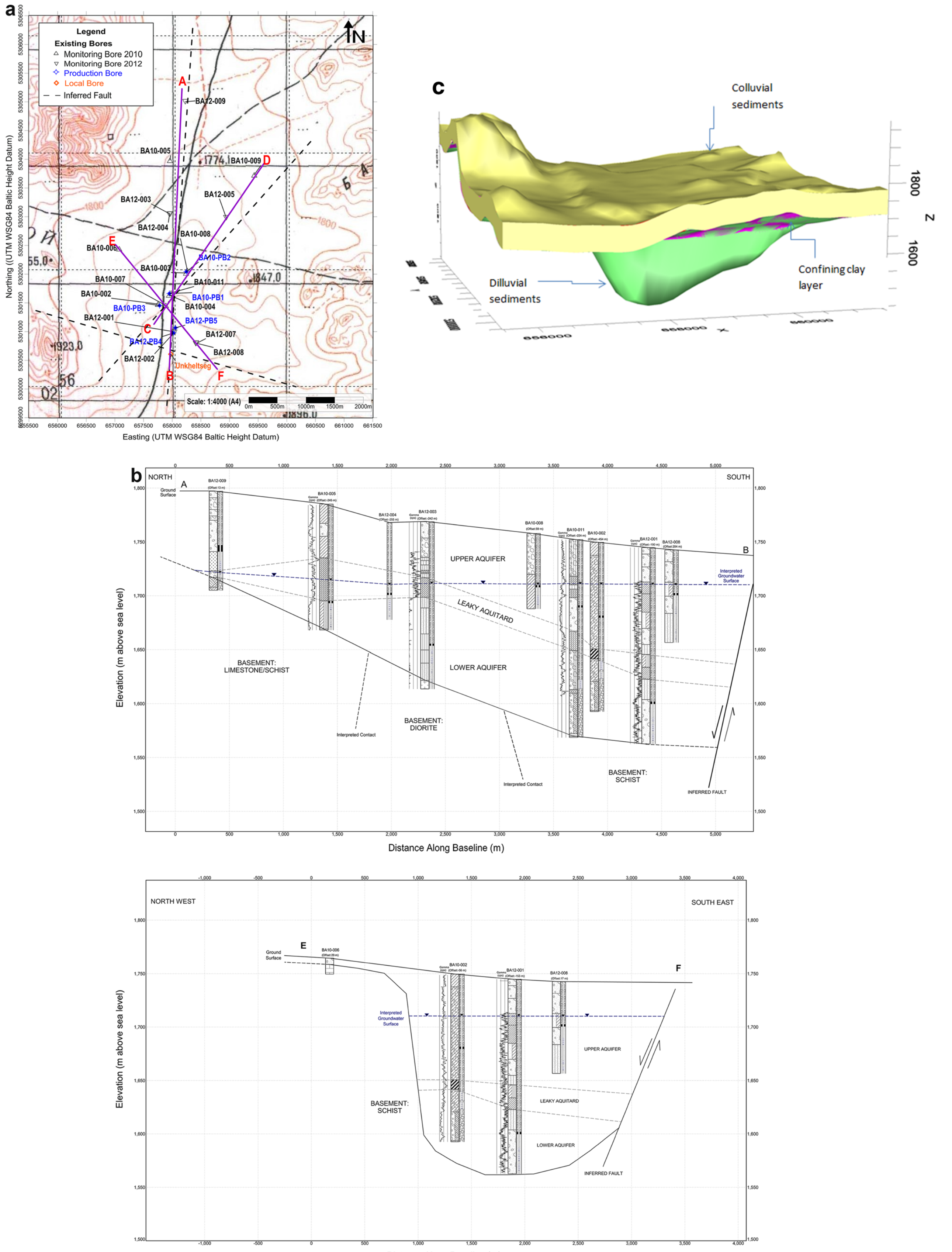

Fig. 3 Location map of the cross section lines (**a**), cross sections (**b**) and 3-D geology of the study area (**c**)

2012) indicated that the upper aquifer is several times more permeable (on average) than the lower aquifer. During the period of the SMEC investigation (2010–2011), the groundwater levels showed very little change suggesting either limited recharge during this period or the control of groundwater level by a spill point through the fault barrier. This spill point controls the maximum groundwater elevation not unlike a dam. Higher groundwater levels in the north of the basin reflect decreasing permeability and likely recharge.

Conceptual model

Models are first and foremost an integration and synthesis of knowledge about a groundwater system allowing one to gain insight into how subsurface flow systems function (e.g. Bredehoeft 2005; Vandenbohede et al. 2011). The conceptual model for the Unkheltseg basin system evolved, as illustrated in Fig. 3, from a basic understanding visualised as a bath tub full of sediment and water that was developed into a conceptual 2-D geological model which became a 3-D geological framework for the numerical simulation. The challenge with the basin model was the limited structural and geological information available. Exploration drill-hole data were combined with interpreted depth to basement from geophysical-induced polarisation surveys, mapped geology and topography to determine the thickness of sediments. Drill-hole data and borehole gamma logs were utilised to interpret the key geological layers and define the upper and lower aquifers.

The approach to creating the geological surfaces used a similar methodology to Danis (2012) in that the layers are created from the interpolation of drill-hole data, geophysical data and mapped surface geology. In complex lithology, such as where there are numerous discontinuous sedimentary layers, to create a 3-D representation that best resembles geological reality requires a degree of simplification to maintain computational ability. Therefore, the basin model was simplified to geological units comprising the key aquifers and aquitard and the basement. Each layer is referenced to the UTM WGS 84 Baltic Height Datum and created using the Kriging algorithm in Surfer^{TM} version 9 (Golden Software Inc) with a spacing of 50 m over the model domain. The surfaces were exported out of Surfer into Hydro GeoBuilder (Schlumberger Water Services 2009) where the surface was created using Kriging interpolation from the irregularly spaced data and then imported into MODFLOW-SURFACT. The model consists of four layers as outlined in Table 3.

Table 3 Model layers

Layer	Description	Thickness
1	Colluvial sediment aquifer	Up to 167 m
2	Semi-confining clay sediments encountered on the east side of the basin	Up to 38 m
3	Semi-confined aquifer within dilluvial sediments	Up to 88 m
4	Bedrock, fractured to some degree	250

Numerical model

Modelling was undertaken using MODFLOW-SURFACT code (HydroGeoLogic Inc 2002), an advanced MODFLOW (McDonald and Harbaugh 1988; Harbaugh et al. 2000), based code developed by HydroGeoLogic Inc. that handles complete desaturation and resaturation of grid cells), within the framework of Visual MODFLOW Version 4.6 (Schlumberger Water Services 2010). MODFLOW-SURFACT solves enhanced equations for performing unconfined simulations to rigorously model desaturation/resaturation of aquifers and overcome numerical difficulties encountered with the previous versions of MODFLOW. In addition, MODFLOW-SURFACT provides a rigorous bore withdrawal package "Fracture-Well Package FLW4" that emulates flow through multi-layer bore. The fracture tube representation allows connection of aquifer cells. Volumetric fluxes from each individual node associated with the fracture are automatically computed by the code, to sum the total drawdown from the bore. In addition, the total withdrawal rate prescribed for the bore is rigorously incorporated. Another feature of FLW4 is that for an overpumped unconfined system, the total bore withdrawal is automatically adjusted when the water level in the well has reached the bottom of the bore.

The model domain for the investigation is a sub-regional area which encompasses the basin (Fig. 1). The actual area modelled was determined during the desktop phase of the model development and comprises a rectangular area of approximately 6 km by 7 km, totalling approximately 43 km^2. The model was designed for steady state and transient state simulation of groundwater flow. A steady-state model was developed first to assess regional flow patterns in the basin aquifers and to calibrate the recharge and transmissivity. Calibration was accomplished, via the trial and error method, by applying a set of hydraulic parameters; boundary conditions and stresses that produce computer-generated pressure heads (or water level drawdowns) that correlate with actual field measurement. A transient model was then developed, using the steady-state

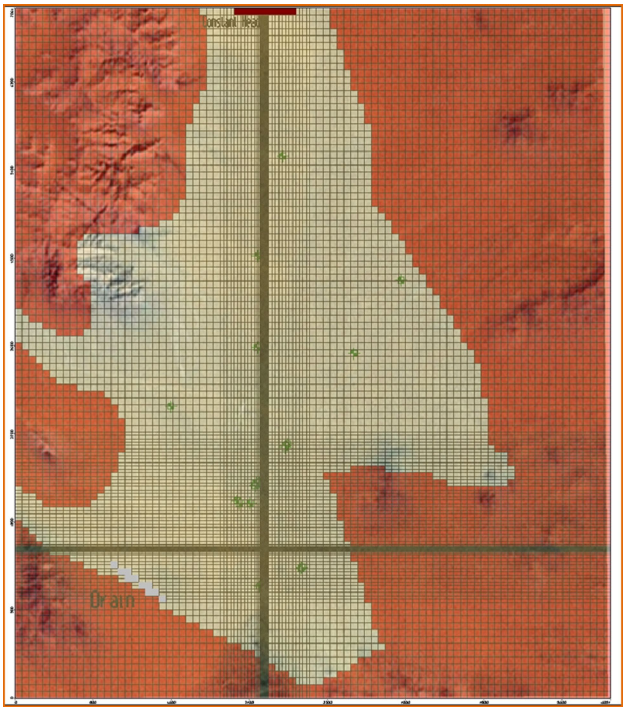

Fig. 4 Groundwater flow model grid. Observation bores are shown in *green symbols*. Drain cells (*grey squares*) and constant head cells (*red squares*)

model hydraulic head output as the initial head to assess potential impacts of extraction/pumping on the groundwater flow pattern based on the measured pumping test data, observation data and 12 months of monitoring data.

Domain and discretisation

The extent of the model domain was based on the appropriate site-specific geological and hydrogeological boundaries. The model domain was designed to reflect the extent of the aquifers that is expected to significantly control the major groundwater flow. The model contains 119 rows by 144 columns giving 68,544 cells. An approximate 70 × 70 m grid was applied across the model area, with refinement of the grid to 5 × 5 m around the proposed pumping bores to allow for the steeper hydraulic gradient near the pumping bores. In the vertical direction, deformed model layers were used to represent the hydrogeological framework in the model (Fig. 3c). Vertical discretisation using deformed model layers allows horizontal continuity to be maintained with fewer cells (Reilly and Harbaugh 2004).The model grid is presented in Fig. 4.

Boundaries

The model area is located between a series of no-flow boundaries. To the east and west, following the surface divide, north is inferred by the absence or thinning of aquifers and south coinciding with the basement high. For the practical purpose of modelling the groundwater system, a generic boundary regime has been adopted, based on the use of upstream and downstream constant head and drain elevation, respectively. Constant head boundary condition of 1,735 m is applied to the north boundary of the model area at the active model cells for layer 3. Drain elevation of 1,710.8 m, with a calibrated conductance value of 100 m^2/day, was assigned for all layers representing the basement high at the southern boundary of the model area. The lowest formation (basement), has very low permeability, and is assigned as inactive cells. The lower no-flow boundary of the model is the bottom of the basement based on the assumption that the low permeability of the basement will allow minimal flow.

DRAIN package

The DRAIN package (McDonald and Harbaugh 1988) is designed to simulate the effects of features such as agricultural drains and geological barriers. The Drain package is used to simulate head-dependent flux boundaries (Harbaugh et al. 2000). In the DRAIN package if the head in the cell falls below a certain threshold, the flux from the drain to the model cell drops to zero. The drain is assumed to run only partially full, so that the head within the drain is approximately equal to the median drain elevation, *di, j, k* [*L*]. The head, *hi, j, k* [*L*], computed by the model for cell (*i, j, k*), is actually an average value for the cell and is normally assumed to prevail at some distance from the drain itself. The drain head, *di, j, k*, prevails only locally, within the drain; it does not characterise the cell as a whole. The drain removes water from the aquifer at a rate proportional to the difference between the head in the aquifer and drain elevation. The drainage continues as long as the head in the aquifer is above the drain elevation, but ceases if the head falls below that level. The functioning of the DRAIN package is described by the equation pair:(McDonald and Harbaugh 1988)

$$QDi,j,k = CDi,j,k(hi,j,k - di,j,k) \quad for\, hi,j,k > di,j,k \tag{1}$$

$$QDi,j,k = 0 \quad for\, hi,j,k \leq di,j,k \tag{2}$$

where *QDi, j, k* [L^3/T] is the groundwater discharge volume flux from cell (*i, j, k*) into the drain; *hi, j, k* [*L*] is the calculated head in cell (*i, j, k*); and *di, j, k* [*L*] is the drain elevation. The coefficient *CDi, j, k* [L^2/T] is a lumped conductance describing all of the head loss between the drain and the region of cell (*i, j, k*) in which the head *hi, j, k* is assumed to prevail. This lumped drain conductance is added to the conductance calculated by the block-centred

Table 4 Calibrated aquifer properties

Layer	Description	Horizontal hydraulic conductivity (m/day)	Specific yield	Specific storage (1/m)
1	Colluvial sediments	0.26	0.02	2E−7
2	Clay aquitard	0.001	0.002	2E−7
3	Dilluvial sediments	0.1	0.004	1E−8
4	Basement—partially fractured	0.0001	0.004	1E−7
4	Basement—limestone	0.06	0.14	1E−7

flow (BCF) package, which is derived from the horizontal and vertical resistance between the node centre of the drain cell and the centres of the adjacent nodes. The summed DRAIN and BCF conductance therefore defines the total resistance to flow of the MODFLOW drain cell. The head losses between the drain and its adjacent cells are caused by convergent flow towards the drain, flow through the backfill material of the drain, and flow through the wall of the drain (McDonald and Harbaugh 1988).

Hydraulic properties

The aquifer properties adopted are either based on the results of the hydrogeological investigation (pumping tests) and data contained in Wenping et al. (2011). Where no data were available, industry accepted values and best estimates were used. Adopted aquifer properties including hydraulic conductivity, storage coefficients and porosity are summarised in Table 4. The aquifer parameters have been estimated using the Cooper–Jacob straight line and distance drawdown methods for non-equilibrium conditions. They provide an assessment of the transmissivity and storage coefficient for the individual bores and regionally perspective. The results are summarised in Table 2. As the discharge rate from each aquifer is unknown it has been assumed that the discharge is either 4 L/s from each or 1 L/s from the lower and 7 L/s from the upper aquifer based on the 2010 pumping test results (SMEC 2011). Assessment using the Aqtsolv Pro 4.0 software indicates the discharge from each aquifer is closer to 1 and 7 L/s based on curve matching (i.e. using these flow rates the curve match is better than using 4 L/s from each aquifer) from the lower and upper aquifers, respectively. Table 2 provides the results of multiple assessment assuming confined and leaky confined aquifers.

For all sediments, the vertical hydraulic conductivity is set at 1/10th horizontal hydraulic conductivity, to reflect the effects of vertical anisotropy caused by layering in sedimentary deposition, as well as layered heterogeneity (Freeze and Cherry 1979; Kazemi 2012). Anisotropy implies that there must be some sort of preferred orientation to either the fractures or the brecciated material within the fault zone that leads to excellent conductivity along the faults. In a direction perpendicular to the fault plane, the conductivity is much lower. Geologically, it is possible that a fault breccia with gouge will behave anisotropically, as clay like within the fault (Lopez and Smith 1996). For the basement, the groundwater flow in the vertical direction is considered higher than in the horizontal direction; therefore, the vertical hydraulic conductivity is set at 10 times of the horizontal hydraulic conductivity. Generic storage terms have been used for all confining and semi-confining layers. In the case of the colluvial and dilluvial aquifers, the storage terms were obtained from either the SMEC (2011, 2012) pumping test results or published literature values of a comparable lithology. To simulate basement aquifer recharge the limestone outcrop west of the basin sector of the model domain was assigned a relatively high permeability, 0.06 m/day.

Recharge, discharge and evapotranspiration

The net recharge to the upper groundwater table at the model area is assumed to be 0.9 mm per annum, 1 % of precipitation based on the characteristic of surface geology and depth of groundwater. The rainfall was used for a transient run, using the monthly time-varying recharge rate from 2010 to 2012 (1 % of monthly precipitation was assumed). Evapotranspiration, given the depth of groundwater, is >15 m below ground level, is not considered to be active.

Steady-state calibration

The model was calibrated by matching observed groundwater heads against predicted heads in 20 bores within the model domain (Fig. 5). To improve calibration, the hydraulic conductivity and recharge zones were adjusted until the modelled head elevations were able to match observed head elevations to an acceptable level of accuracy.

The results of the calibrated head versus the observed head of layer 1 and 3, which have a correlation coefficient of 0.98, a root mean squared error of 0.45 m and residual mean error of 0.11 m, are considered to be very good. The baseline gradient and flow are in a southerly and south westerly direction through the aquifer. Based on these results, it is considered that the model realistically simulates the groundwater elevation and flow direction across the model domain.

Fig. 5 Potentiometric surface—steady state (*arrow flow direction*) and observation piezometer (*green*) layer 1—colluvial sediments and layer 3—dilluvial sediments respectively

Table 5 Modelled mass water balance summary for steady state

Component	Inflow (m^3/day)	Outflow (m^3/day)
Recharge	3.5	0
Drain		9.5
Through flow (constant head)	6	0
In–out: 0.0 m^3/day		
Discrepancy: 0 %		

The volume of water entering the basin aquifers is mainly through rainfall recharge with some through bedrock flow. The simulation shows that the flow system conserves mass (Table 5) i.e. the volume of water entering the model through recharge and through flow equals the volume that leaves the model through drainage representing the basement high. The groundwater level at the fault barrier is at an elevation of 1,710.8 m, with a calibrated conductance value of 100 m^2/day.

Overall, model calibration is considered acceptable on the basis of the correlation coefficient (0.98), mass balance discrepancy (0.02 %) and spatially random residual error (Barnett et al. 2012).

Transient state calibration and simulation

Calibration: observed head

The transient state calibration aims to achieve a difference of ±0.5 m between the modelled and observed head drawdown. Fluctuation of the drawdown is mainly caused by the fluctuation of recharge, drainage at the fault barrier and applied constant head condition.

Calibration: pumping test data

Pumping tests were conducted by SMEC (2012) to evaluate the aquifer hydraulic conductivity and storage coefficient for transient model calibration. Field pumping tests were run for 10 days with one production bore discharging 8 L/s, on average, and 10 observational piezometers. Here the model simulates the water level drawdown over a period of 26 days, with 10 time steps and a time step multiplier of 1.2. Aquifer parameters were adjusted in the model manually to match the observed drawdown for a short transient event. Results of the modelled drawdown versus observed drawdown show that there is a good match after about 10 days but initially the match is not as good which is likely a result of the storage properties. According to Middlemis (2004) regional model should not be expected to exactly reproduce local-scale changes in head response to pumping.

The value in any model comes from analysing the sensitivity of parameters to change to see what effect such changes may have on the model results. The sensitivity of recharge and permeability was assessed and the results, Figures. 6 and 7 were plotted against mean absolute error in metres. Most sensitive to change was the hydraulic conductivity of layers 1 and 2 and, as anticipated, recharge. Drain conductance, specific yield and specific storage were sensitive to a lesser degree.

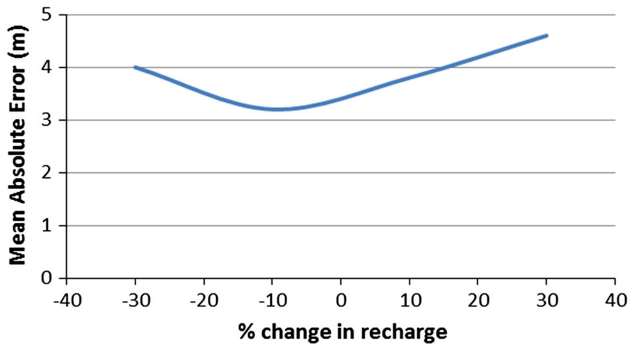

Fig. 6 Sensitivity analysis for recharge

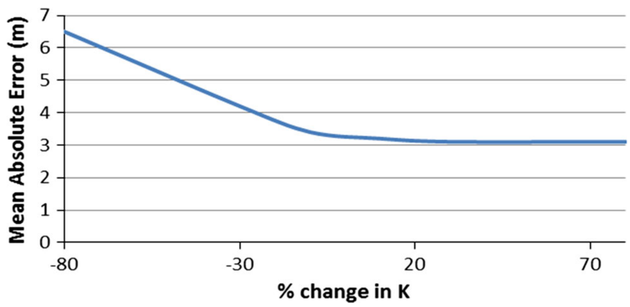

Fig. 7 Sensitivity analysis for conductivity *K* of layers 1 and 2

Simulation

The transient simulation, to estimate the effects of mine groundwater extraction was run for 7 years beginning in the year 2000 and ending in 2012. It used a monthly time-varying recharge rate that of 1 % of monthly precipitation and the hydraulic conductivity and storage coefficient values of Table 4. The scenario is as follows: rotating pumping from three bores for 7 years with a variable pumping rate ranging from 4.2 to 17 L/s (Table 6) to meet mine demands and a 20-year post-pumping recovery period.

Groundwater extraction from the upper and lower aquifers in the basin was simulated with the transient state runs predicting water table and piezometric surface drawdown for layers 1 and 3, respectively, after 7 years (Fig. 8) and 20-year post-pumping period (Fig. 9).

Simulation results

The maximum predicted water level drawdown within the monitoring piezometer model cell at the end of 7 years pumping is around 72 m. The radius of influence from the pumping bores is of the order of 5 km after 7 years of pumping (Fig. 8). Note that for layer 1 the cells in the central and northeast of the model area went dry as a result of pumping. For layer 3, only few cells in the northeast went dry. The maximum head drawdown in layer 1 (the colluvial aquifer) is approximate 20 m after 7 years pumping as shown in Fig. 8 and the total head drawdown for the Unkheltseg bore (a local stock bore), located in the south of the Basin is estimated to be approximately 13 m.

Table 6 Proposed monthly mine water demand at a variable pumping rate ranging from 4.2 to 17 L/s for 7 years

Month	Pumping bore volume (L/s)			Total (L/s)
	PB1	PB2	PB5	
January	7	0	8	15
February	9	0	8	17
March	8	0	8	16
April	0	0	8.5	8.5
May	0	0	7.5	7.5
June	0	5.5	0	5.5
July	0	4.2	0	4.2
August	0	4.2	0	4.2
September	0	5.2	0	5.2
October	6.5	0	0	6.5
November	7.5	0	0	7.5
December	7.5	3	0	10.5

The post-recovery contours (Fig. 9) show that even after 20 years the groundwater table will not be fully recovered. For layer 1 there would be recovery of around 13 m out of the 20 m of drawdown or 65 % after 20-year post-pumping.

The numerical results show that, based on the average mine water demand of 9 L/s (2.83×10^5 m^3/year), the hydrogeological impact after 7 years of pumping will be lowering of the water table by 20 and 72 m within the colluvial upper aquifer and the dilluvial lower aquifer, respectively.

Model results indicate that pumping induces a decrease in groundwater storage with long-term water level recovery of 65–85 % after 20 years for the shallow and deep aquifers, respectively. This indicates vertical movement of water from layer 1 due to leakage to the underlying aquifer (layer 3); and impacts to base flow to the Zavkhan River are likely to be negligible.

Model limitations

The model includes assumptions based on the literature values and the experience of the modeller.

Limitations exist with respect to:

- aquifer recharge rates and spatial distribution of aquifer recharge areas;

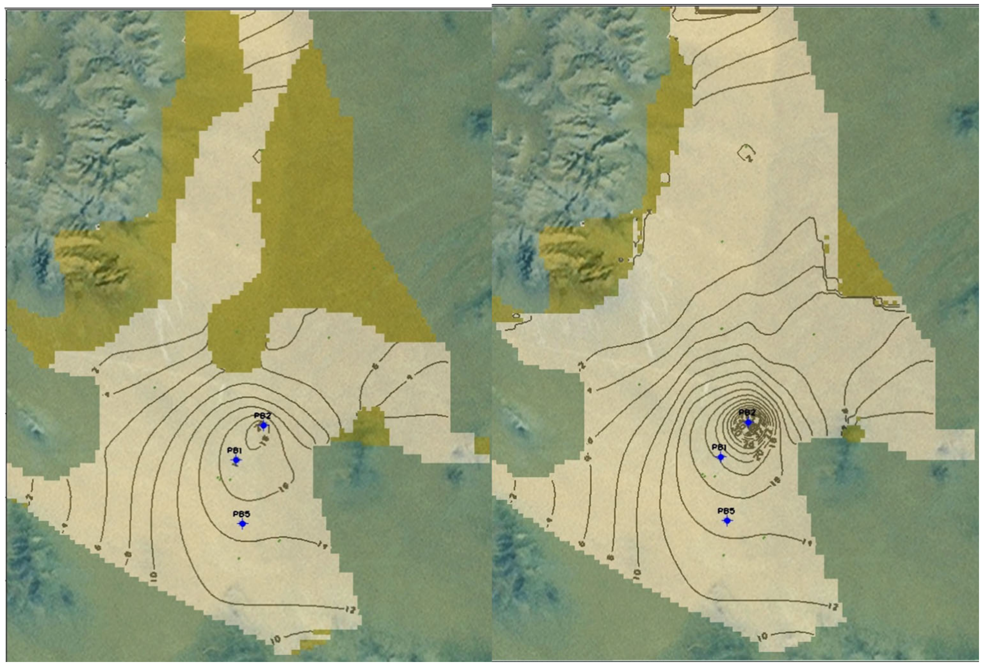

Fig. 8 Drawdown (m) map of the model area, after 7 year—(end of pumping). Layer 1 and layer 3

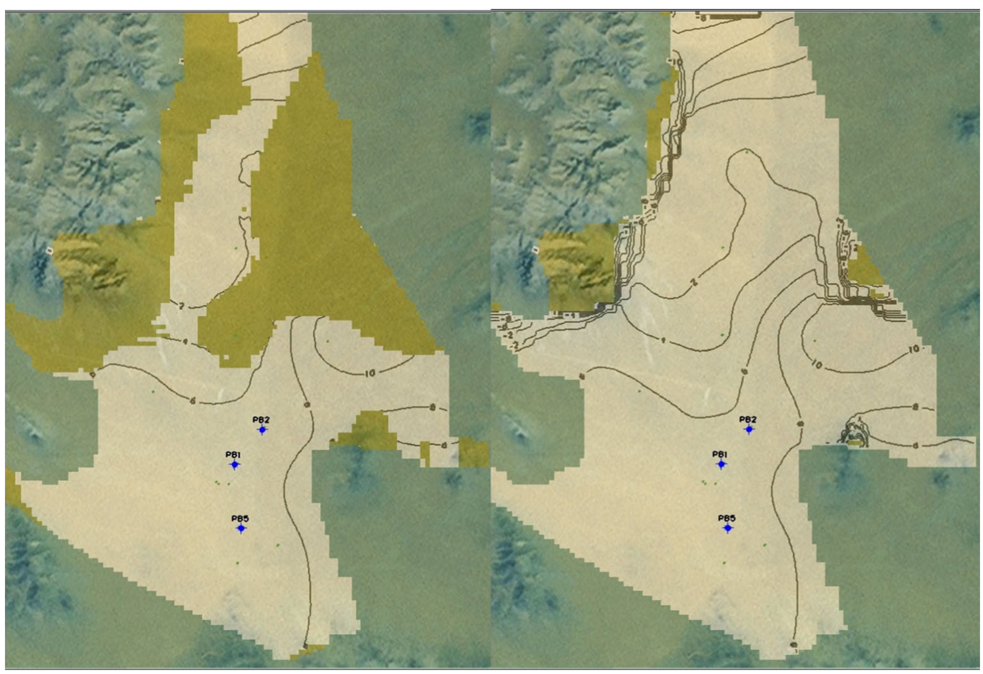

Fig. 9 Drawdown (m) map of the model area, after 20-year post-pumping—layer 1 and layer 3. Note that the reduction in drawdown (due to recovery for 20-year post-pumping) comparing with the Fig. 8 (end of the pumping time)

- hydrogeological properties of limestone and basement rock units; and
- structural influence on groundwater flow (faults, fractures and joints).

The current model assumes limited rainfall recharge of 1 % of precipitation, discharge controlled by geology with a set invert point and limited influence from the underlying and surrounding bedrock. The large limestone located on the northwestern side of the basin may provide a significant amount of water. However, only long-term pumping and monitoring will allow assessment of the influence of these factors and the level of conservativeness of the adopted model parameters. Groundwater recharge is rarely well defined (Voss 2011). Initial head data are related to the time span of observations used for calibrating the transient state model. Data from two hydrological years have been used, as no longer term data were available; and this may be a source of uncertainty since long-term fluctuations may not have been observed.

The geological data and measurements used in creating this model are spatially limited within the Unkheltseg Basin and this should be taken into account when assessing the results.

Conclusions

In large arid or semi-arid inland basins in Mongolia and China, reverse faults, parallel to the mountain strike in general and having significant vertical displacement, make the groundwater level in the Quaternary aquifer systems differ by 100 m or more on the two sides of the fault. There is no direct hydraulic connection between the two sides and a groundwater fall occurs across the fault. The downstream aquifer system has enough capacity to accept the lateral discharge from the upstream side, and this means that the recharge to the downstream aquifer system is equal to the discharge of the upstream aquifer system. The discharge or recharge amount is decided only by the permeability and hydraulic conditions of the upstream aquifer system. Simulation of the upstream aquifer system (and hence a groundwater fall formed by faults) has become an interesting challenge in regional groundwater modelling. The Unkheltseg Basin is an example of an unusual geologically constrained groundwater resource located in the Taikh Valley in northern Mongolia. This resource is critical for economic development in the region but previous assessments had been limited to the analytical interpretation of pumping test data. With no direct hydraulic connection between the two parts of the basin system, groundwater recharge from Unkheltseg Basin to the Tost Basin is controlled geologically across the fault and may only occur when the groundwater table in the Unkheltseg Basin is at a specific level.

For effective groundwater management on a regional scale, a calibrated 3-D numerical simulation was required to assess both the ability of the resource to supply mine demand and assess the potential impacts of such extraction activities. Producing a calibrated and validated groundwater model increases confidence in the conceptual model of the main physical processes and forces that are controlling hydraulic heads and fluxes. Model sensitivity analysis is a useful tool for identifying the most critical parameters of the hydrogeologic system to ensure appropriate field monitoring. The approach in this case identified the need for explicit spatial discretization and full representation of horizontal and vertical flow directions at the south end of the Unkheltseg Basin as the key factors necessary to constrain the recharge area and assess and quantify the groundwater dynamics. Changing stresses, such as increasing recharge, only slightly affect the simulated water table as the controlling factor is the threshold discharge level across the fault barrier.

Accurate regional groundwater models that predict regional impacts are an important management tool in countries like Mongolia who have a high dependence on groundwater. Groundwater models are important tools for demonstrating a qualitative and quantitative understanding of a hydrogeological system that is consistent with the current available data. This model showed that short-term high-intensity extraction would affect a large area over a very long period of time. Whilst the Bayan Airag mine is currently the only mine planning to extract water from this basin system, there are already stock and domestic users of the groundwater resource. The model demonstrates how existing users will be impacted and where future potential users may also be impacted highlighting the importance of proper long-term aquifer management strategies.

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