REPORT

Hydrogeology of an arid endorheic basin (Tsagaan Els, Dornogobi, Mongolia): field data and conceptualization, three-dimensional groundwater modeling, and water budget

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Abstract

The Tsagaan Els basin is a ~16,300 km^2 endorheic basin located in the Gobi Desert in Mongolia. This Cretaceous sedimentary basin is crossed by the North Zuunbayan fault, which determines two partially connected hydrogeological sub-basins: Zuunbayan and Unegt. Two roll-front uranium ore deposits have been discovered in these sub-basins by Orano Mining and its subsidiary COGEGOBI LLC, and the regional aquifers have been surveyed for several years. Based on that knowledge, this study presents the regional hydrogeological functioning of this multi-layered aquifer system supported by a regional groundwater model. The latter was implemented with MODFLOW and calibrated through PEST using piezometric levels. Recharge rates were adjusted to between 0.6 and 3.1 mm/year. The resulting water budget indicates an important transfer of water from Unegt sub-basin toward Zuunbayan sub-basin, occurring at a few main springs located along the North Zuunbayan fault. Evaporation loss is potentially high during these transfers but the remaining water seeps through and later evaporates in the depression located at the center of Zuunbayan sub-basin, which is the terminal discharge playa of the entire basin. These results can be helpful for future water management plans.

Keywords Mongolia · Arid regions · Groundwater recharge/water budget · Numerical modeling · Mining

Introduction

Mongolia has tremendous mineral resources in terms of both varieties and quantities (Xun 2017). A good example is the Tsagaan Els basin that encompasses the Unegt and Zuunbayan sub-basins, located in South Mongolia (Prost 2004). Two oil fields are present in its center and the recent exploration work conducted by Orano Mining and its subsidiary COGEGOBI LLC have led to the discovery of two important roll-front uranium deposits (Cardon et al. 2015). These deposits are planned for mining using an in-situ leaching method. Therefore, the regional aquifers have been carefully surveyed for several years to ensure the applicability of the method without harming the environment.

Water management is an important issue in arid/semi-arid areas, as water is usually present in limited supply and aquifers do not replenish as fast as in humid regions (Colby and Jacobs 2006). Moreover, these systems are sensitive to climate change (Lioubimtseva and Henebry 2009; Wang and Qin 2017) and additional direct anthropic pressure could have severe environmental, social and economic impacts (Sefelnasr et al. 2015; Wang and Qin 2017)—for example, too much pumping could lead to groundwater/surface-water depletion which may in turn affect the local communities and endemic biodiversity (Davis et al. 2017; Decuyper et al. 2016; Foster and Chilton 2003). A general picture of the hydrogeological functioning of the basin is therefore a prerequisite to ensure the long-term water needs of everyone, but such studies are often limited by the lack of data (García-Rodríguez et al. 2014).

Regarding the hydrogeology of the Tsagaan Els basin, Mongolian and Russian experts have conducted local water

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supply studies throughout the 1980s and 1990s (Nemer and Tuinhof 2010), but an overview of the regional hydrogeology had never been presented before. The objectives of this study are:

1. To present the current understanding of the hydrogeological functioning of the basin at a regional-scale based on recent observations (geographic information systems (GIS), water levels and exploration)
2. To develop a numerical model based on this conceptualization to establish a regional water budget and to extend knowledge of piezometry and water fluxes

This work was a necessary step to optimize the future mining projects and to control their environmental impacts. Groundwater quality will not be dealt with here but will be detailed and discussed in a separate paper.

Description of the study area

The Tsagaan Els basin refers to the drainage basin of the eponymous depression (fig. 1). It is located in the province of Dornogobi in Mongolia and is part of the South Gobi Desert. Between 1,500 and 3,000 people live in the area according to the density of inhabitants given by the 2010 national census. The economy relies on the mining industry and on tourism, but nomadic livestock herding remains historically the main activity of the region. The basin is a typical Central Asian desert, sparsely vegetated with grass and saxaouls (*Haloxylon ammodendron* an endemic shrub) and with local sand dunes several meters high. The basin consists of a depression with a lower point around 700 m and peripheral highs that can reach 1,400 m. It is an arid/semi-arid area with a continental climate. Average annual temperature is around 6–8 °C with large annual variation going from up to 40 °C in July to as low as −35 °C in January. Average annual precipitation is ~110 mm with a third of it falling in July during rainstorms. Potential evapotranspiration was estimated at 1,450 ± 200 mm/year between 2014 and 2017 at the Dulaan Uul exploration camp weather station (Davis Vantage Pro2 using Penman-Monteith equation). These conditions prevent the existence of permanent surface water except at a few springs located along the North-Zuunbayan fault. The basin is part of the Central Asian internal drainage basin (Tsogtbaatar et al. 2009) and its endorheic nature is both due to its topography and current climatic conditions.

The Tsagaan Els basin is a continental sedimentary basin, part of the larger East-Gobi basin (Graham et al. 2001; Johnson 2015; Johnson et al. 2001). The major North Zuunbayan fault crosses the basin and delineates two sub-basins: Unegt (NW) and Zuunbayan (SE; Figs. 1 and 2). The other major faults are the Zuunbayan fault (also called

East-Gobi Fault Zone) located in the south of Zuunbayan sub-basin and the North Unegt fault zone, NW of the Unegt sub-basin. Three large sand/conglomerate aquifer systems separated by semi-continuous clay layers of various thicknesses have been discovered in the Late Cretaceous formations named Bayanshiree (K2Bs), Upper Sainshand (K2Ss2) and Lower Sainshand (K2Ss1). Locally, Quaternary aquifers also exist but have not been studied because of their limited spatial extent. These hydrogeological units are discussed in the following and their thickness and permeability are presented in Table 1.

The K2Bs formation is a continuous sandy aquifer in the Zuunbayan sub-basin that can be either confined or unconfined depending on the presence of upper impervious clay layers. In the Unegt sub-basin, this formation is mostly composed of clays with limited sandy horizons that can constitute only localized aquifers.

- The K2Ss2 formation is a multilayer aquifer with partially connected units named U_{0-3} in the Zuunbayan sub-basin and U_{1-4} in the Unegt sub-basin (Fig. 2). All the units are mostly confined and of good permeability.
- The K2Ss1 formation is a confined aquifer of good permeability in the Unegt sub-basin only. In most of the Zuunbayan sub-basin, this formation is mostly composed of clay but can present some local confined aquifer units.

The hydrogeology has been carefully studied on the exploration licenses through a monitoring network of more than 150 wells mainly intercepting the different aquifer units of the K2Ss2 but also of the K2Ss1 and K2Bs formations. Small variations of the hydraulic head observed at each piezometer have been shown to result from atmospheric pressure variation, while no sizeable variation linked to seasonal precipitation has been found. Spatially however, significant variation of hydraulic head exists (Fig. 3), and water salinity variation is also important (1–20 g/L). For this reason, a salinity correction based on the method of Bachu and Michael (2002) was used to visualize flow direction correctly in Fig. 3. The average salinity of each sub-basin was used as a reference and all levels were corrected by comparison with the top of K2Ss2 aquifer. These corrections are negligible in Unegt sub-basin but can reach up to 3 m in the Zuunbayan sub-basin.

In the Unegt sub-basin, the groundwater of all aquifers flows toward a spring called Baruun Bayan (BB) with an average hydraulic gradient of ~0.2‰. Part of the flow may also reach the Dund Bayan spring (DB). Recharge seems to occur both from the north and west side of the sub-basin.

In Zuunbayan sub-basin, the groundwater flow of both K2Ss2 and K2Bs aquifers is directed toward the Tsagaan Els depression and their piezometric levels align themselves with the elevation of this topographic low area. This suggests a configuration where water infiltrates on the border of the basin
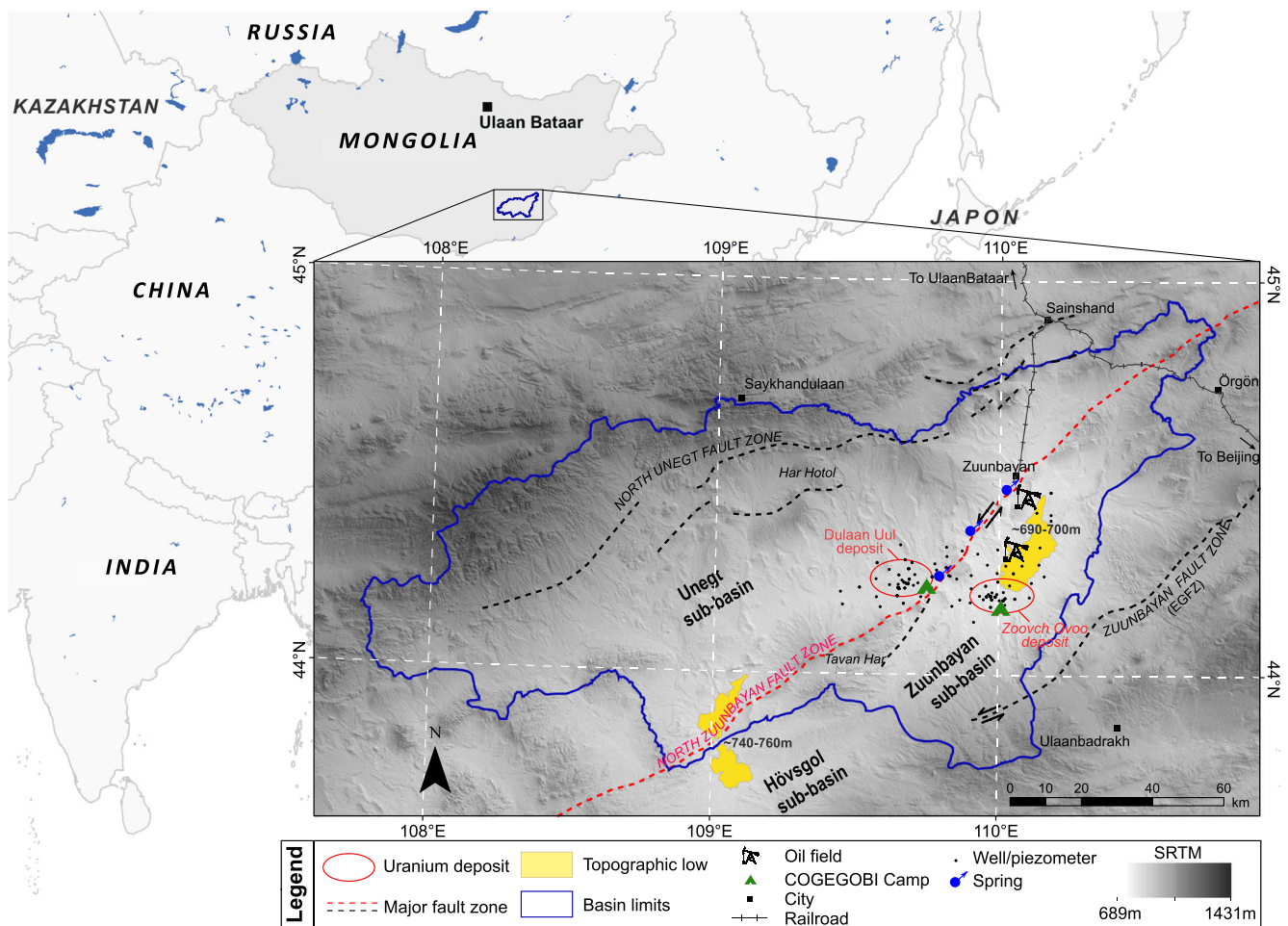
Fig. 1 Geographical context of the Tsagaan Els basin with main structural features

and discharges in the center through subsurface evaporation in the upper aquifer. K2Ss2 aquifer is artesian in this central area and the only way out for K2Ss2 groundwater is to flow upwards through sedimentary layers. The hydraulic gradient is 0.2‰ in the K2Bs aquifer and 0.1‰ in the lower K2Ss2 aquifer.

Materials and methods

Basin conceptualization

A conceptual model of the basin is required in order to develop a regional groundwater flow model. This phase mainly consists in delineating the basin, locating the potential outlets and understanding the hydrogeological role of the North-Zuunbayan fault.

Basin delineation

The basin delineation is based both on the topographic and geological features. Connections with other basins are

possible, especially on the eastern side but are assumed negligible for the purpose of this study. The drainage area covers ~16,300 km^2 unevenly distributed between the Zuunbayan (~4,000 km^2) and Unegt (~12,300 km^2) sub-basins.

Basin outlets

In endorheic basins, water leaves the basin only via evaporation. This massive water loss happens in the central topographic depression as well as in smaller local depressions where humid areas can usually be found. Because of the extensive size of the basin, these zones have been detected based on hydrologic data and satellite images (Fig. 4a,b). Four humid zones have been identified as potential outlets of the basin—Fig. 4, more details are given in the electronic supplementary material (ESM). They are dry most of the year but some local temporary lakes may form after heavy rain in summer and disappear within a few weeks.

- Zone 1 is the major central Tsagaan Els depression with a flat topography at 700 m above sea level (a.s.l.) which can locally go as low as 695 m a.s.l. Its surface covers 180 km^2
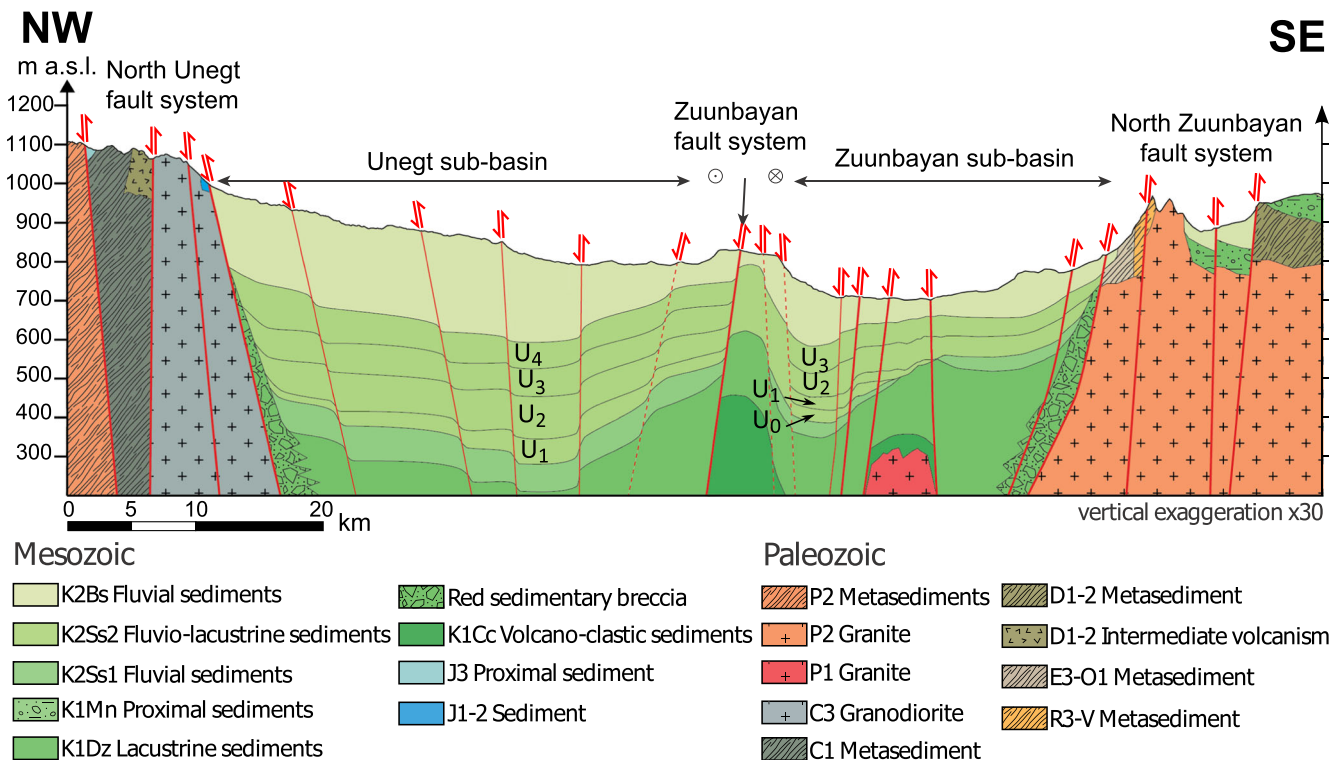
Fig. 2 Schematic NW–SE cross-section of the Tsagaan Els basin showing the Unegt and Zuunbayan sub-basins general morphology (Orano/COGEGOBI document, see Fig. 3 for location of cross-section)

when considering the 700 m a.s.l. contour line. Several wadis, coming from all directions are draining into this area.

- Zone 2, north of Zuunbayan city, has an inclined topography that goes from ~755 m a.s.l. at the south close to the city up to 800 m a.s.l. in the northern part. Only one wadi which drains a large portion of the north of the basin, flows into this zone.
- Zone 3 is located in the center of the Unegt sub-basin and drains a large portion of its central part. Its elevation goes from 790 m a.s.l. on the western side to 760 m a.s.l. on the eastern side.
- Zone 4, SE of the Unegt sub-basin, is mostly flat with an elevation between 754 and 760 m a.s.l. The drainage area of this ~56 km^2 zone is important and covers a large portion of the western side of the basin.

Zones 1 and 4 are presumably playas (Briere 2000). These areas correspond to groundwater outlets where the shallow water table enables subsurface evaporation and preservation of the sediments against wind erosion up to the capillary fringe (Warren 2016); therefore, the topography in these zones is controlled by the water table and appears flat (Fan et al. 1997; Rosen 1994). Zone 1 is regarded as an active *terminal discharge playa*, according to the classification of Rosen (1994), as it is the lowest area of the entire Gobi basin and all groundwaters seem to converge toward it (Fig. 3). Zone 4

on the other hand may correspond to a *through-flow playa* as it is not the ultimate outlet of Unegt sub-basin. Zones 2 and 3, which present an inclined topography, are probably *recharge playa*s (Rosen 1994), also known as *dry playas* (Reynolds et al. 2007). These zones are dominated by surficial flows and may correspond to a preferential location for groundwater recharge. The observed groundwater level of K2Ss2 aquifer in zone 3 is at least 10 m below the topography which confirms that this type of playa cannot discharge any water.

The main central depression (zone 1) is dry most of the year except after heavy summer rains suggesting a system dominated by groundwater rather than surface water. This is confirmed using the classification of Bowler (1986) and the low disequilibrium index (−300/−900%) found using the equations proposed in that paper. Such systems are usually expected to present very high groundwater salinity (~250 g/L) especially at the top of the aquifer, which leads to specific density-driven flows (Fan et al. 1997; Simmons 2005). Yet, the salinity measured in the few wells intercepting K2Bs/K2Ss2 aquifer within the playa does not go above 2/8 g/L respectively and no salt crust covers the playa. Whether convective flow can develop with such low concentrations is unlikely but higher salinity values occurring near the water table may foster such phenomenon at a local scale. Considering how stratified the system is, this high salinity water may remain on top of clay layers in the upper portion of the K2BS aquifer and not be seen by the current piezometric network.

Table 1 Average thickness and hydraulic conductivities of the different units in the Upper Cretaceous

Code formation	Code aquifer	Average thickness (m)		Hydraulic conductivity	
		Zuun	Unegt	Zuun	Unegt
K2Bs	U_{K2Bs}	60	65	High	Medium[a]
K2Ss2	U_0	20	NA	High	NA
	U_1	25	33	High	High
	U_2	63	64	High	High
	U_3	62	70	High	Medium
	U_4	NA	89	NA	High
K2Ss1	U_{K2Ss1}[b]	>130	243	Low	High

The thickness of the different units is based on the log database of Orano. The qualitative values for hydraulic conductivity are based on pumping tests and, when not available, on observed facies. *NA* not applicable; *Zuun* Zuunbayan

[a] Locally high but globally low

[b] K2Ss1 consists of a thick clay formation in Zuunbayan sub-basin

Role of the North-Zuunbayan fault

Unegt and Zuunbayan sub-basins are separated by the North-Zuunbayan fault. The 50 m difference between the piezometric levels of Unegt and Zuunbayan sub-basins clearly suggests that the fault acts as a flow barrier. Yet these two sub-basins are undeniably connected. Firstly, the only potential discharge playa found in Unegt sub-basin (zone 4) is not big enough to be the only outlet of the sub-basin. By comparison, the Tsagaan Els depression (zone 1) is more than three times the size of zone 4 and is located within a sub-basin that is four times smaller. Therefore, part of Unegt's groundwater is likely to reach Zuunbayan sub-basin. Several springs systematically appearing at an elevation close to 760 m a.s.l. have been found along the North-Zuunbayan fault (Fig. 3). They are named from south to north: Baruun Bayan spring (BB), Dund Bayan spring (DB) and Zuunbayan springs (ZB). Groundwater flow direction deduced from the piezometric map in Fig. 3 shows that BB is one of the outlets of the Unegt sub-basin and it is reasonable to assume the same for DB and ZB. The water flows from these springs into the Zuunbayan sub-basin most of the year (except during the frozen period from approx. November until March) and surficial connections therefore exist between the two sub-basins.

Groundwater model

A three-dimensional (3D) regional groundwater flow model based on the previous observations has been developed using MODFLOW-2005 (Harbaugh 2005) via Visual MODFLOW 2009 (version 4.4.0.156). The geological model used was developed by Orano using seismic lines, geological maps and numerous technical logs. Only the main Upper Cretaceous aquifer (K2Ss1, K2Ss2 and K2Bs) is considered. Local Quaternary aquifers have been neglected at this scale. All

aquifers are separated by a semi-impervious clay layer. The different units of the K2Ss2 aquifer have been merged together to be simulated as one aquifer. This assumption is compatible both with the purpose of this regional model and data obtained throughout the licenses. Indeed, specific conductivities and piezometric levels from the corresponding wells strongly suggest that the different units of the multilayer K2Ss2 aquifer in both sub-basins are locally interconnected especially in Zuunbayan sub-basin and in the upgradient portion of Unegt sub-basin.

Simulations were conducted under steady-state condition because of the absence of seasonal variations of the piezometric level and under the assumption that current groundwater flows were not influenced by paleoclimatic conditions. The transient assessment behavior framework proposed by Currell et al. (2016) applied with the characteristic of the basin validates this last hypothesis.

Density-driven flow was not considered at this stage due to the need to limit the computational requirement of the model. The groundwater salinity range observed in Unegt sub-basin is quite narrow and not taking this type of flow would have a negligible effect. On the other hand, the central part of Zuunbayan sub-basin, where evaporation takes place, may be affected by such flow as discussed before. Yet, it is supposed to have a limited impact at a regional scale because the extent of this unusual flow is either restrained to local area and/or limited to the upper part of the K2Bs aquifer. Hydraulic head distribution in this area may therefore differ but the impact on the regional water budget would be limited.

To facilitate the calibration process the model was divided into two sub-models: one for each sub-basin. The extent of the hydrogeological model was truncated (~1,000 km²) as the 3D geological model did not cover the entire basin. This extent was further reduced due to the dry-cell problem specific to MODFLOW (Doherty 2001; Painter et al. 2008). Recurrent
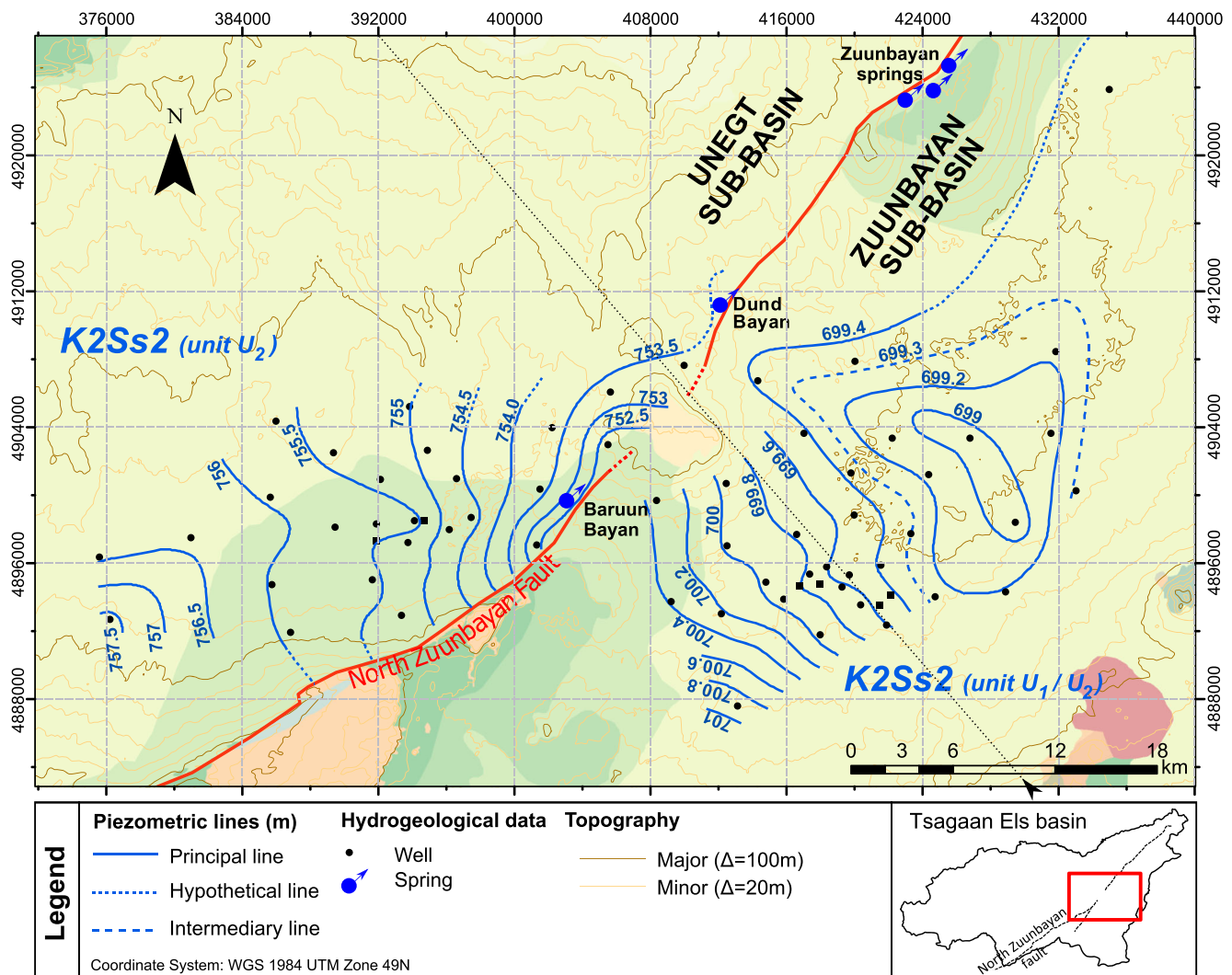
Fig. 3 Piezometric map of the unit U_2 of Unegt sub-basin and U_1/U_2 of Zuunbayan sub-basin. The legend of the geological map in the background is given in Fig. 2. The piezometric values have been corrected based on their salinity before being interpolated manually. The average salinity of each sub-basin was used as the reference salinity and levels were corrected using the top of K2Ss2 aquifer as a reference level following the method of Bachu and Michael (2002)

dry cells at the border of each sub-basin were set inactive to overcome this issue. Even though no flow is computed within these truncated areas, the water coming from it is considered using specified flow boundaries (Fig. 5).

The outlets of the basin were defined with constant head and drain conditions. The use of evaporation boundaries with the evapotranspiration package (EVT) in MODFLOW (Harbaugh et al. 2000) led to convergence issues and was therefore replaced by simple drain conditions. Such replacement has a negligible impact on the steady-state piezometric levels. The maximum depth of active evaporation has been adjusted manually to 1 m in all conditions. In reality, this process can happen even deeper, up to more than 2 m (Fontes et al. 1986; Harrington et al. 2002; Houston 2006) but a value of 1 m led to better agreement in most cases. This difference may be caused by the exponential decrease

of evaporation rate with depth that is not simulated with these boundary conditions (Shah et al. 2007). The model characteristics are summarized in Table 2 and Fig. 5.

Calibration method

The two models were calibrated independently with PEST (Doherty 2005) using an objective function, φ, based on data from the piezometric network (Eq. 1).

$$\varphi = \sum (h_{obs} - h_{calc})^2$$
h_{obs} : observed head (m)
h_{calc} : calculated head (m)
$\qquad$ (1)

A total of 41 and 45 calibration points were used for Unegt and Zuunbayan sub-models respectively. These points consist
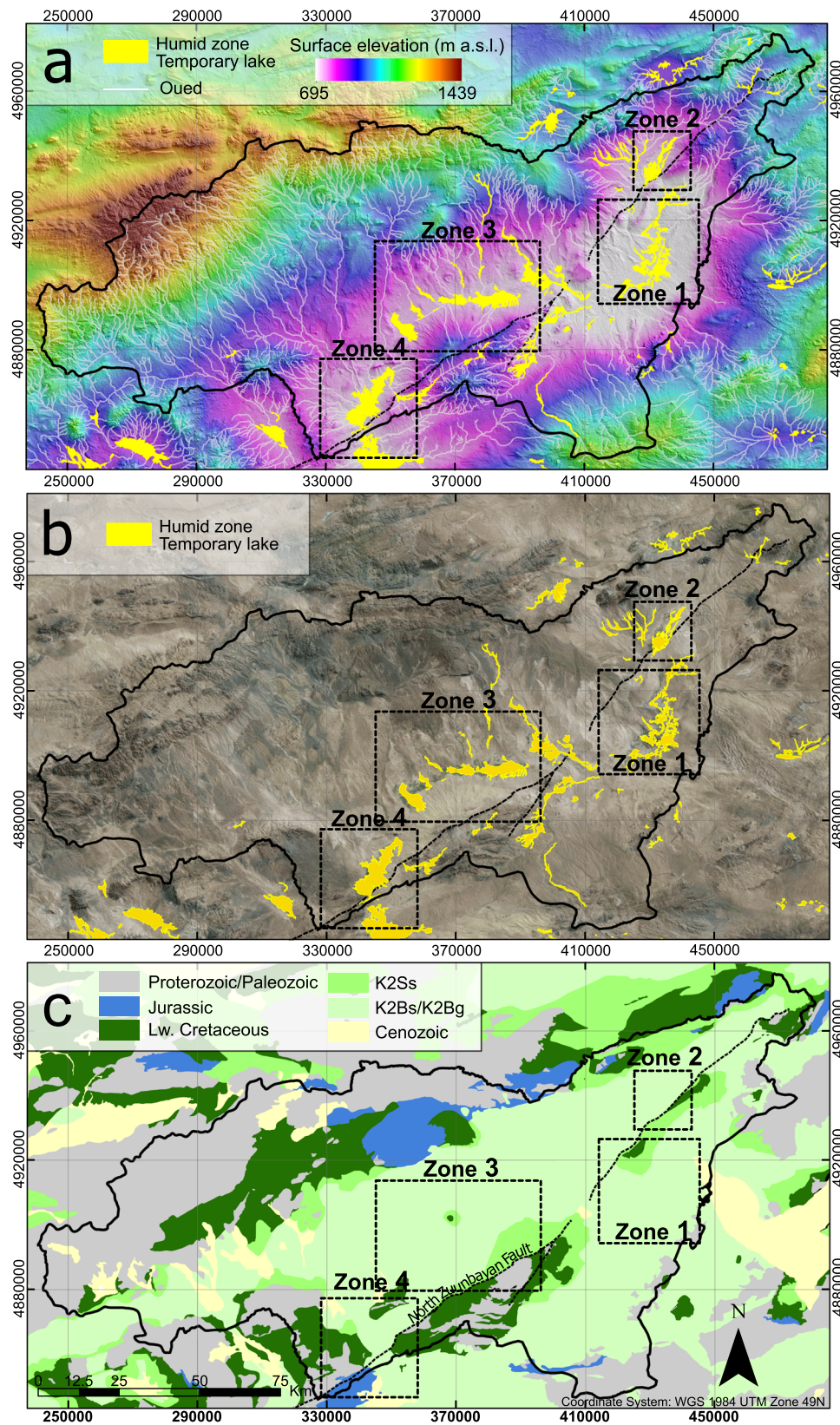
Fig. 4 Hydrographic network combined with **a** topography, **b** satellite imagery, and **c** geology. The extents numbered 1–4 represent potential basin outlets and are discussed in the text. Maps in the ESM describe more accurately each of these zones. The satellite imagery is from ArcGIS Online basemaps and includes multiple sources (Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, and the GIS User Community)
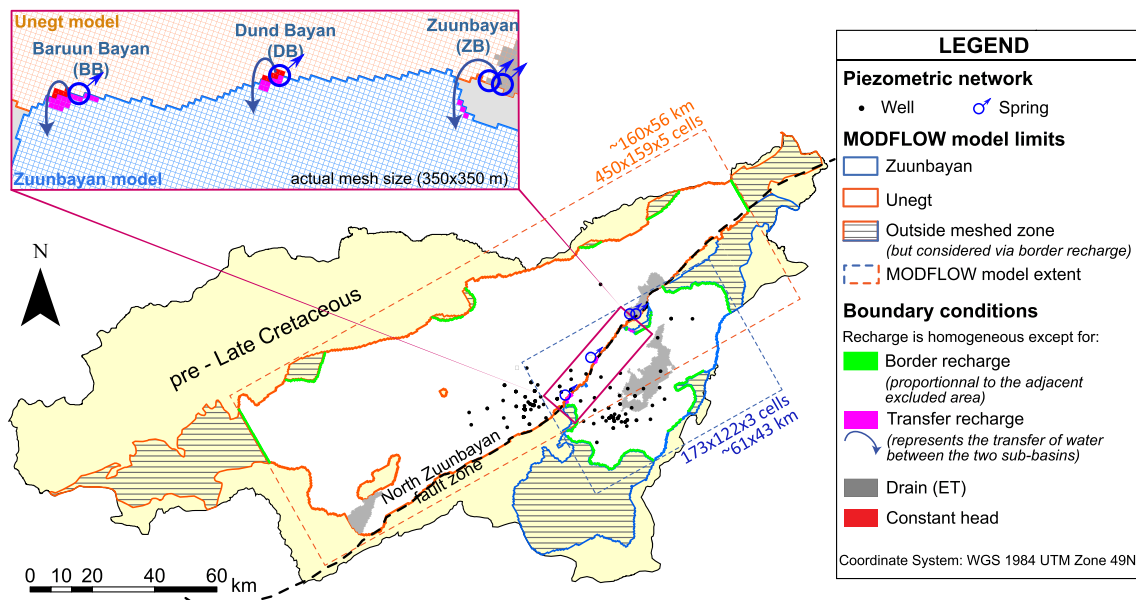
Fig. 5 Model extent and boundary conditions for the Unegt and Zuunbayan sub-models
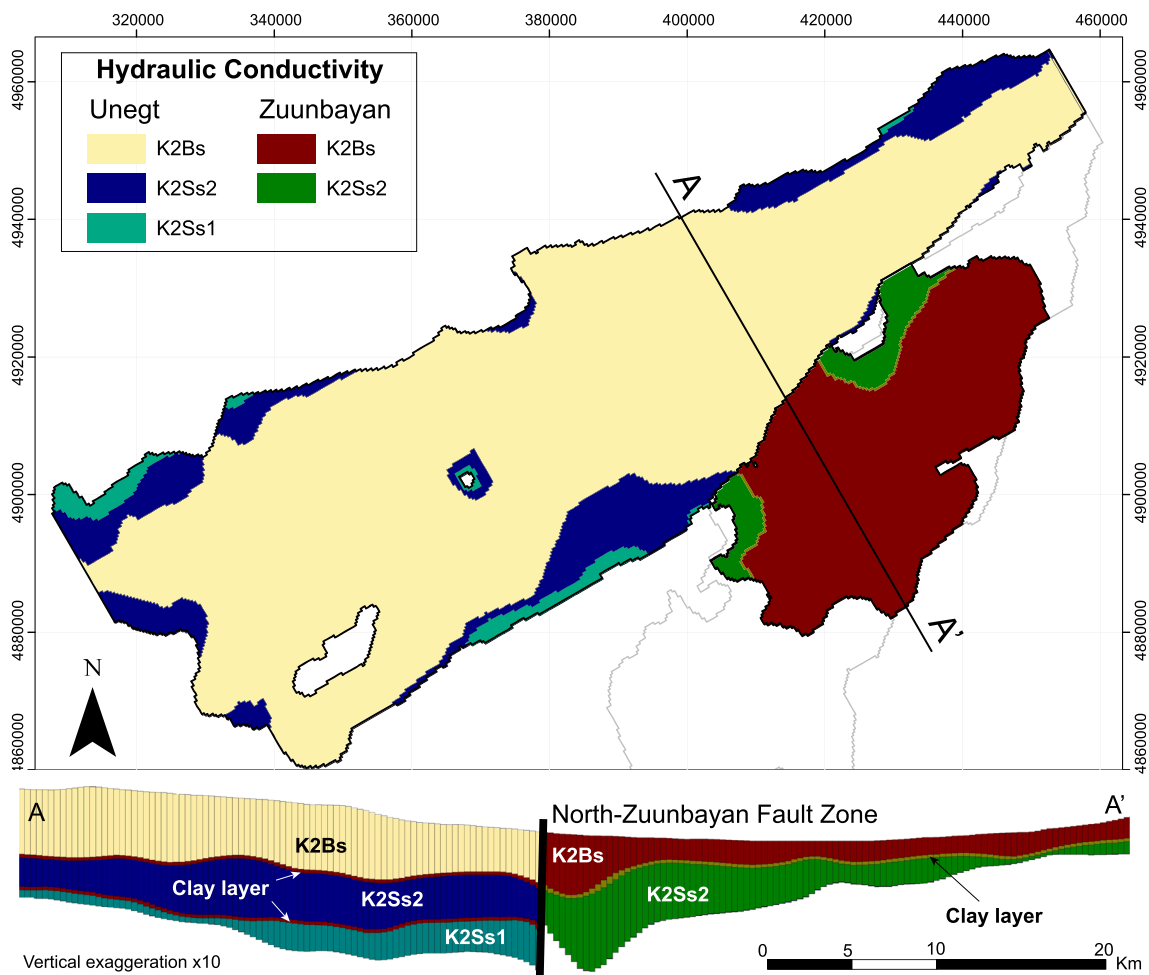

Fig. 6 Aerial view of the upper layer and cross section of the model displaying the different geological units. Each unit has uniform hydraulic conductivities with isotropic properties except in the vertical direction ($K_x = K_y = 0.1\ K_z$). Intermediate clay layers have total isotropic properties

Table 2 Summary of models characteristics

Models characteristics	Description
General	• Two models, one for each sub-basin • Simulated with MODFLOW 2005 (Harbaugh 2005) via Visual MODFLOW 2009 under steady-state condition • No density-driven flow considered
Geological model	• Developed by Orano
Spatial discretization	• 350×350 m cells with 5 and 3 layers giving a total of ~212,000 and ~35,000 active cells for Unegt and Zuunbayan sub-basins respectively
Hydraulic conductivity (K)	• Parameter supposed spatially uniform for each formation (see Fig. 6) • $K_x = K_y = 0.1\,K_z$ (except for intermediate clay layer where $K_x = K_y = K_z$) • Parameters adjusted through calibration but constrained by field data (e.g., pumping test, Table 3).
Recharge (R)	• Recharge assumed to be diffuse and uniform on each sub-basin. • Parameters adjusted through calibration but constrained by literature values
Evapotranspiration and discharge	• Constant head imposed at BB and DB springs • Drain conditions in zones 1 and 4 of Fig. 4 and around the Zuunbayan springs (Fig. 3) at a depth of one meter below the top of the cell
Water transfer	• Water transfer from Unegt toward Zuunbayan sub-basin assumed to take place at the surface of the different springs along the North-Zuunbayan fault. Specific recharge values were therefore set downstream of these springs (see Fig. 5)

of piezometric levels measured in October 2015 with a correction based on the water salinity (Bachu and Michael 2002). Drain boundary conditions may overestimate water removal in the central depression when applying salinity correction because the corrected level is higher than the uncorrected one. To limit this effect, the reference salinity for Zuunbayan sub-basin was taken as the average of every well *within* the depression. Such correction was unnecessary for Unegt sub-basin because of the lower salinities involved. When nearby wells intercept the same aquifer (i.e. nested piezometers, pumping well), their levels were averaged and considered as one unique data point. Six wells (discussed later in the results section) were not considered in the calibration process because modeling has been unable to reproduce their piezometric level probably as a result of specific local conditions.

The different parameters to consider for calibration are listed in Table 3, with their respective interval of variation. Hydraulic conductivity extrema were based on the different estimations obtained from pumping tests. In the absence of reliable data as for the clay layers and K2Bs formation in the Unegt sub-basin, the interval was adjusted manually with reasonable values and a larger range.

Table 3 Parameters description and interval of variation

Region	Model parameters	Observed data range	PEST Variation range
Unegt	Hydraulic conductivity (m/s)		
	K2Bs	4.0×10^{-6} ($n = 1$)	10^{-8}–10^{-4}
	K2Ss2	$3.3 \times 10^{-6} - 2.8 \times 10^{-3}$ ($n = 28$, 2.5×10^{-4})	10^{-5}–10^{-3}
	K2Ss1	$4.6 \times 10^{-5} - 1.8 \times 10^{-3}$ ($n = 2$)	10^{-5}–10^{-3}
	Intermediate clay layers	NA	10^{-10}–10^{-6}
	Recharge rate (mm/year)	NA	0.2–5
Zuunbayan	Hydraulic conductivity (m/s)		
	K2Bs	$1.4 \times 10^{-5} - 2.5 \times 10^{-4}$ ($n = 11$, 8.5×10^{-5})	$5 \times 10^{-5} - 5 \times 10^{-4}$
	K2Ss2	$2.2 \times 10^{-6} - 9.6 \times 10^{-4}$ ($n = 32$, 1.2×10^{-4})	$5 \times 10^{-5} - 5 \times 10^{-4}$
	Intermediate clay layers	NA	10^{-9}–10^{-7}
	Recharge rate (mm/year)	NA	0.5–5
	Flow coming from:		
	BB spring (m³/year)	NA	0–3.97×10^{6} [a]
	DB spring (m³/year)	NA	$\propto Q_{BB}$
	ZB springs (m³/year)	NA	0–4.70×10^{6} [a]

Hydraulic conductivities have been obtained using Lefranc tests and 72-h pumping tests. The number of observed data and the mean value are given between brackets. Recharge rate values come from literature reviews (refer in the main text).

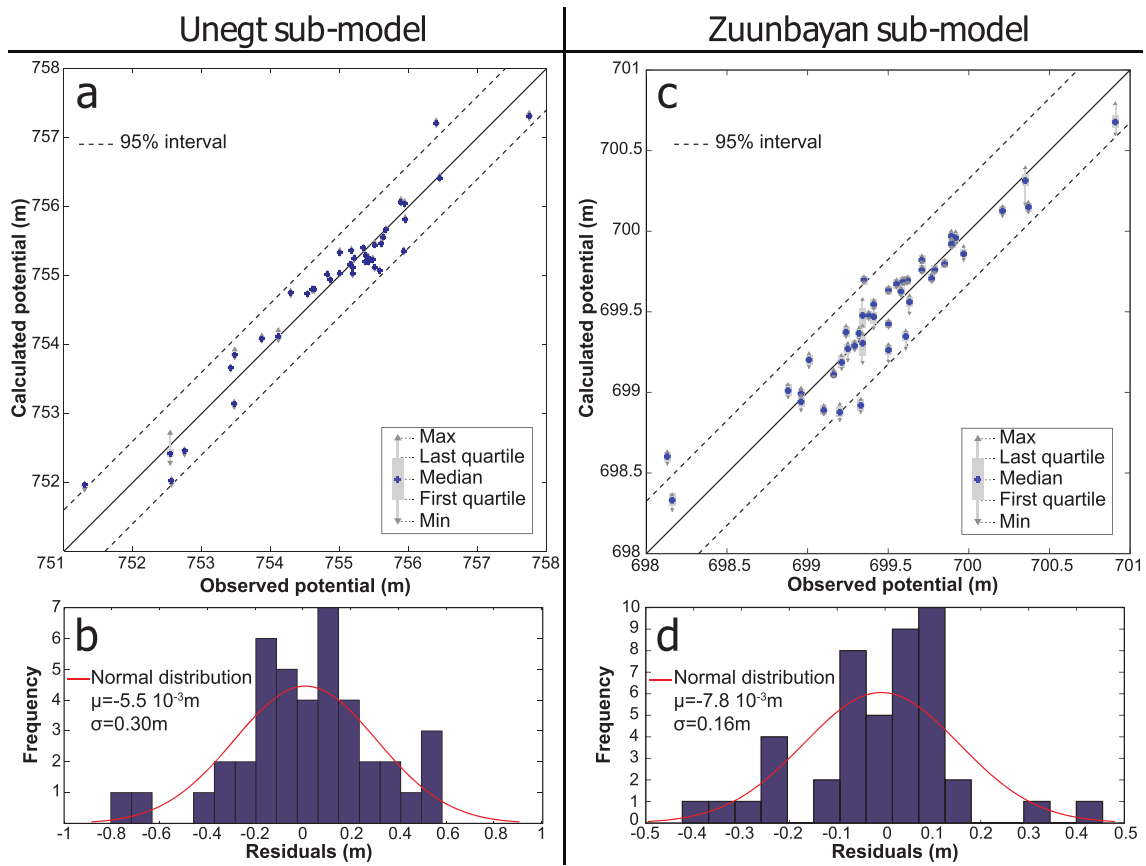[a] Average outflow obtained from Unegt sub-model calibration

Fig. 7 Simulated data versus observed data (**a** and **c**) and histogram of the residuals (**b** and **d**) for Unegt and Zuunbayan sub-models respectively
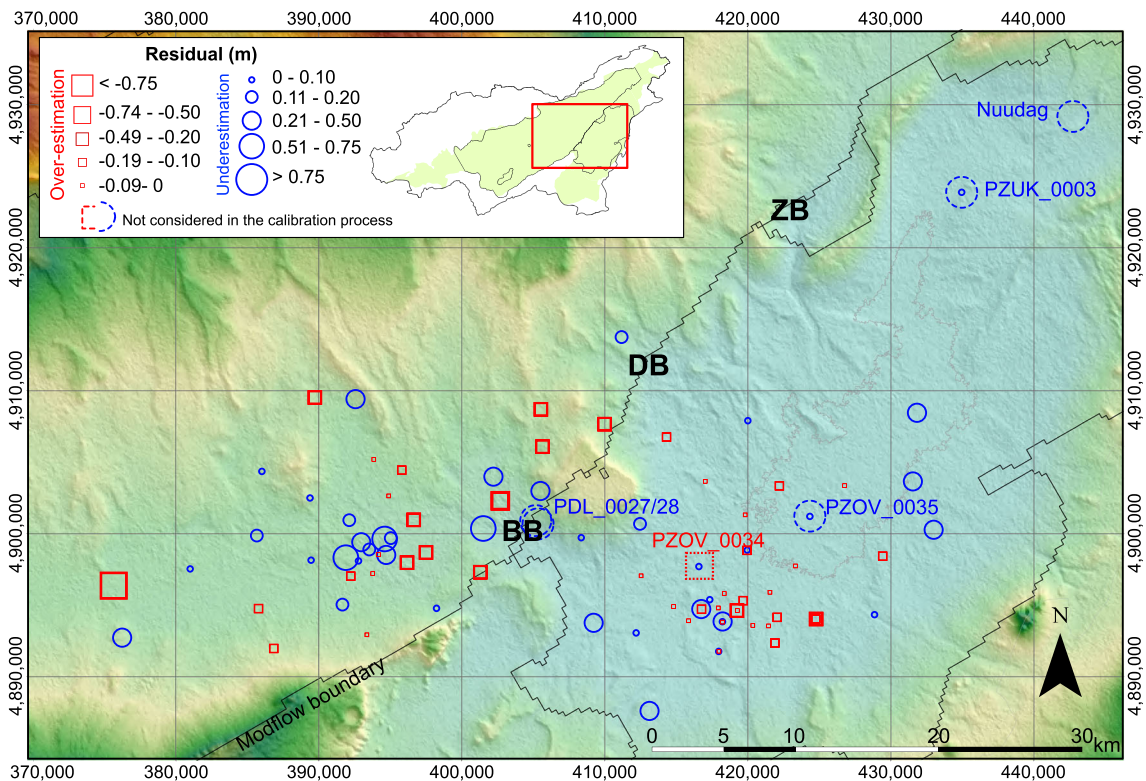

Fig. 8 Spatial distribution of the residuals

Table 4　Parameters range after calibration and average relative sensitivity

Region	Model parameters	Pest lower bound	Simulated data			Pest upper bound	Average relative composite sensitivity[a]
			Min	Median	Max		
Unegt	Hydraulic conductivity (m/s)						
	K2Bs	10^{-8}	4.7×10^{-6}	2.3×10^{-5}	4.4×10^{-5}	10^{-4}	1.52
	K2Ss2	10^{-5}	2.4×10^{-5}	6.0×10^{-5}	1.2×10^{-4}	10^{-3}	5.28
	K2Ss1	10^{-5}	1.7×10^{-4}	4.9×10^{-4}	8.7×10^{-4}	10^{-3}	0.42
	Intermediate clay layers	10^{-10}	4.3×10^{-9}	1.2×10^{-8}	2.4×10^{-8}	10^{-6}	2.32
	Recharge rate (mm/year)	0.2	0.6	1.7	3.0	5	0.86
Zuunbayan	Hydraulic conductivity (m/s)						
	K2Bs	5×10^{-5}	5.0×10^{-5}	8.8×10^{-5}	1.8×10^{-4}	5×10^{-4}	1.46
	K2Ss2	5×10^{-5}	1.9×10^{-4}	3.1×10^{-4}	5.0×10^{-4}	5×10^{-4}	0.68
	Intermediate clay layers	10^{-10}	2.6×10^{-9}	4.2×10^{-9}	8.4×10^{-9}	10^{-6}	3.41
	Recharge rate (mm/year)	0.5	1.1	1.8	3.1	5	0.15
	Flow coming from						
	BB spring (m³/year)	0	5.4×10^{5}	1.3×10^{6}	2.1×10^{6}	4.0×10^{6}	0.70
	DB spring (m³/year)	0	2.2×10^{5}	5.3×10^{5}	8.3×10^{5}	1.6×10^{6}	
	ZB springs (m³/year)	0	3.5×10^{5}	1.8×10^{6}	4.6×10^{6}	4.7×10^{6}	0.70

[a] The relative composite sensitivity of a parameter is a measure of the composite changes in model

No studies have been conducted to estimate the recharge rate but literature regarding nearby deserts has been investigated. The recharge rate varies between 0.8 and 3.6 mm/year (1–4% of annual precipitation) in the Badain Jarain Desert (Gates et al. 2008; Jin et al. 2015; Ma et al. 2008) and between 0.9 and 2.5 mm/year (<1–2% of annual precipitation) in the Tengger Desert (Ma et al. 2009). These deserts are located ~800 km SW of the study area in Inner Mongolia (China) but have a quite similar environment. In a broader approach, recharge rate in watersheds larger than 40 km² located in arid/semi-arid regions is about 0.1–5% the value of annual precipitation (Scanlon et al. 2006); therefore the recharge rate in the Tsagaan Els basin was supposed to be in the range of <1–5 mm/year.

Some parameters are not sensitive enough to be calibrated independently; thus, the flow coming from DB spring to Zuunbayan sub-basin has been set proportional to the one coming from BB spring. The proportionality coefficient was based on the total flow coming out of these springs obtained from the Unegt sub-model calibration. Flows coming from ZB springs were not merged with the other two springs, as the water transfer at these locations was supposed to be more prone to evaporation.

PEST does not always converge toward the same solution at each calibration procedure mainly because both hydraulic conductivity and recharge are adjusted together. A sampling set of solutions was captured by launching the PEST calibration procedure several times with randomly chosen initial parameters. The resulting solutions were statistically equivalent even though their parameters values were different. Recharge rates were highly correlated to the hydraulic conductivities of all aquifer as expected (Carrera and Neuman 1986; Knowling and Werner 2016) and doing more calibrations was judged unnecessary as extremum parameters value were already reached. The nonuniqueness issue could have been reduced using flow estimation at the sub-basin's outlets (Arnold et al. 2000) but such data are unavailable when surficial flow is almost nonexistent. Springs along the fault are the only exceptions but they unfortunately cannot be gauged due to their swampy environment.
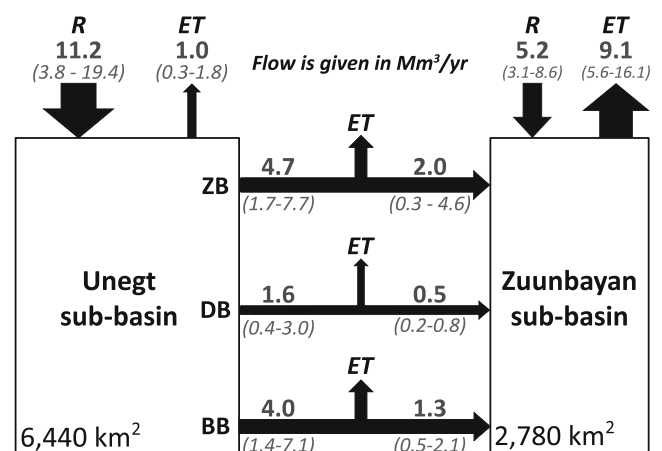

Fig. 9 Water balance model of the Tsagaan Els basin. For each flow component, the minimum, average and maximum values of all calibrated simulation results are given

Results and discussion

Calibration results

After 15 PEST calibration runs, 13 solutions have been selected for Unegt sub-model with an objective function comprised between 3.5 and 3.7 m^2. Two runs converged toward a local minimum with a greater φ value (5.9 and 7.4 m^2). For Zuunbayan sub-model, the representativeness of the sampled set was increased by picking two solutions for each run: one is the optimal solution found, usually with a φ value around 1.15 m^2, and the other is the first solution found to have a φ value below 1.21 m^2. Results of these calibrations are displayed in Fig. 7 and indicate a good agreement between observed and simulated data. The residual distribution ($h_{\mathrm{obs}} - h_{\mathrm{calc}}$) is visually similar to a normal distribution and error appears randomly distributed. The Nash-Sutcliff coefficient is equal to 0.94 and 0.95 and the average absolute residual error is 22 and 12 cm in Unegt and Zuunbayan sub-basins respectively. Among the different calibrated solutions, residual variation at each observation point remains low.

Residuals, whether positive or negative, increase around BB spring in the Unegt sub-basin (Fig. 8). The north-eastern part of this sub-basin seems well simulated according to the two nomadic wells. The two most remote wells in the western part show high residuals, both positive and negative. Yet they are located only 4 km apart and intercept the same aquifer. This large difference may correspond to a local recharge coming from the south.

In the Zuunbayan sub-basin, residuals are smaller. They tend to be slightly overestimated south of the playa and underestimated elsewhere in the sub-basin. Six observation points have been deleted from the calibration process because of a PEST convergence problem. These points are located in Fig. 8 and underline the limits of this regional model. PDL_0027 and 28 are located downward of the North-Zuunbayan fault and their observed levels (~734 and 720 m a.s.l. respectively) are still highly influenced by the water transfer from Unegt sub-basin. PZOV_0034 and 35 intercept the K2Bs aquifer and local recharge and evaporation is thought to be the reason of these 1 m errors. The NE of the basin is underestimated according to Nuudag well and PZUK_0003. This part of the basin has not been studied as thoroughly as the rest and a possible connection with another basin or a difference in hydrodynamic properties may explain these errors. Also, Nuudag is a nomadic well whose level value may have been influenced by undocumented pumping prior to measurement.

Parameter values and regional water balance

The parameters derived from the calibration are summarized in Table 4. The upper K2Bs aquifer and the underlying K2Ss2 aquifer have lower hydraulic conductivities in Unegt sub-basin compared to Zuunbayan sub-basin. This result was expected for the K2Bs aquifer but not for the K2Ss2 aquifer which presents similar facies and pumping test results. Hydraulic conductivity of the semi-impervious clay layers in-between aquifers is low, as expected, but is also the most sensitive model parameter. The results also show that in both sub-basins, the deeper the aquifer, the higher the hydraulic conductivity.

Recharge rate is similar in both sub-basins and ranges between 0.6 and 3.1 mm/year (Table 4). Over the entire basin, this represents a volume of water entering the system between 6.9 and 28 Mm^3/year This estimation could be refined by measuring local recharge rate in several key locations using adapted methods—i.e. chloride mass balance (Gates et al. 2008; Jin et al. 2015; Ma et al. 2008) coupled with remote sensing data (Brunner et al. 2007, 2004; Coelho et al. 2017; Hendricks Franssen et al. 2008). Nevertheless, this first result suggests that water supply in the Tsagaan Els basin seems sufficient enough to cover the current anthropic activities at a regional scale. Water quality, on the other hand, should be more emphasized, as the hydrochemical studies conducted in nearby or broader areas usually indicate a chemical composition that does not meet the standard for domestic use (Jia et al. 2017; Munkbaatar et al. 2008; Nemer and Tuinhof 2010; Nriagu et al. 2013).

The water budget of each sub-model has been further studied through the different outflows and inflows (Fig. 9). Water infiltrates mostly in the Unegt sub-basin, which is more than two times larger than Zuunbayan sub-basin. The playa of Unegt sub-basin (zone 4, Fig. 4) only evacuates between 5 and 9% of this infiltrated water. Most of the water leaves the sub-basin through ZB springs (38–45%), BB spring (33–37%) and DB spring (10–15%). These diffuse springs cannot be gauged and thus, these results cannot be verified quantitatively. Qualitatively, the satellite images and the different visits in the field through the years only show that DB spring is the smallest one in terms of flow. BB and ZB springs cannot be compared easily because of their different morphology. Large amounts of water are lost by evaporation during the transfer toward the Zuunbayan sub-basin at these three locations. This loss is roughly estimated between 60 and 70% by looking at average values between Unegt's outflows and Zuunbayan's inflows; however, these terms vary over a wide range of values (Fig. 9), which makes this loss estimation coefficient uncertain, especially when looking at each spring individually. The remaining unevaporated flow still represents 34–49% of all the water inputs in the Zuunbayan sub-basin and is almost as important as direct diffuse recharge. The
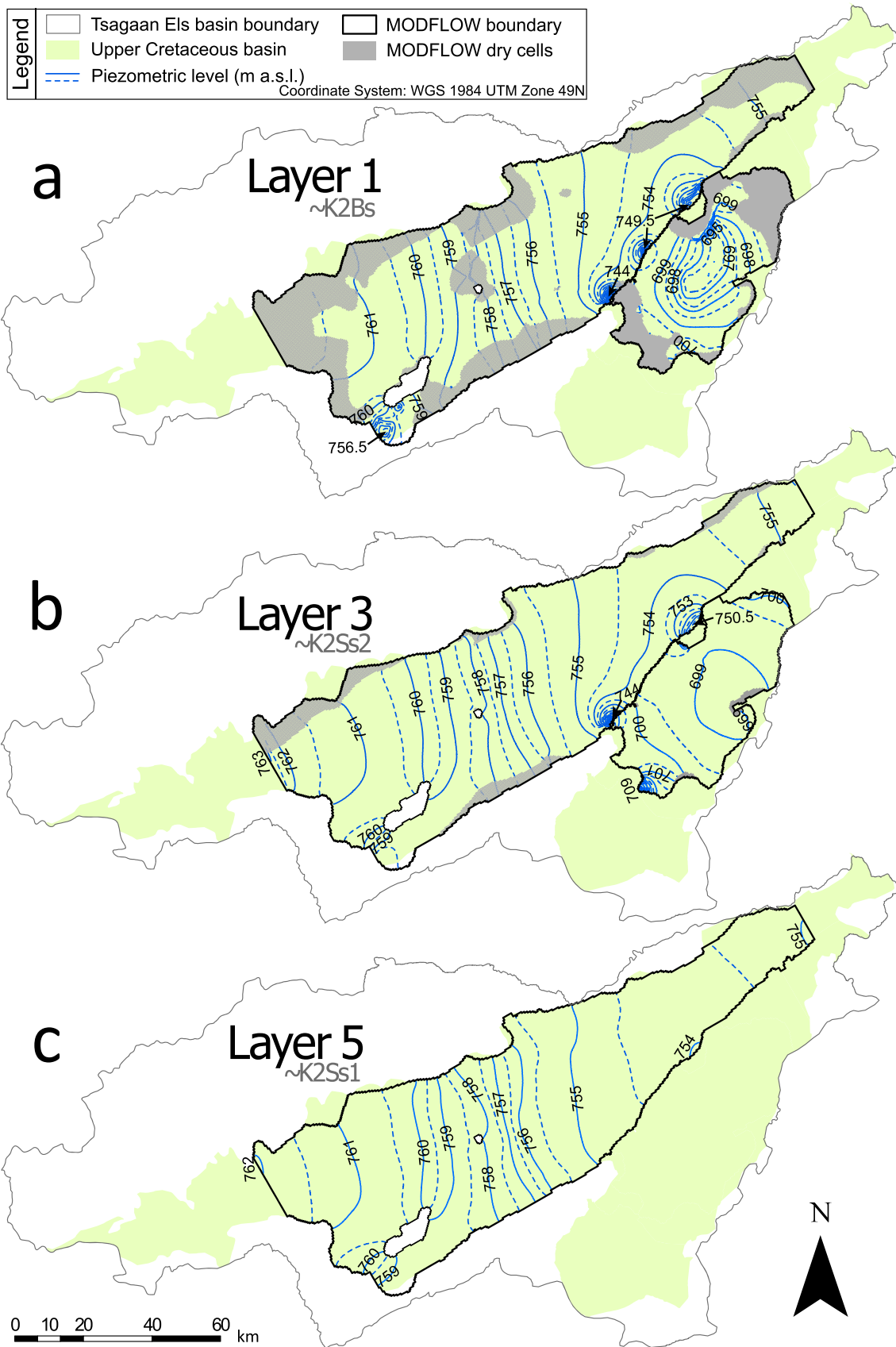
Fig. 10 Average simulated piezometric map of the **a** layer 1 (upper layer), **b** layer 3 and **c** layer 5 of Unegt and Zuunbayan sub-models

Tsagaan Els depression (zone 1, Fig. 4) evacuates all the remaining water, which confirms its role as terminal discharge playa.

The simulated evaporation rate in both discharge playas varies between 140 and 230 mm/year on average among the calibrated solutions and locally does not exceed 1,450–1,700 mm/year. These values are consistent with the fact that the playa remains dry most of the year, as the observed potential evaporation is close to these values (1,450 ± 200 mm/year).

Simulated piezometric maps

Several piezometric maps have been obtained by averaging the different calibrated solutions that presented very similar results (Fig. 10). These simulated piezometric levels are based on the assumption that hydraulic properties and recharge are spatially uniform within each sub-basin. A significant discrepancy may therefore exist with the true levels, especially in the isolated parts of the basin where no data are available. Nevertheless, these maps can still be of use for future exploration programs.

In the Unegt sub-basin, piezometric levels go from ~762 m a.s.l. at the SW border and 755 m a.s.l. at the NE border toward ~750 m a.s.l. near the springs. Flow direction is similar in all aquifers except in the vicinity of outlets. The hydraulic gradient is likewise similar in the different aquifers but varies spatially from 0.01‰ in the NE, which is the deepest part of the basin, to 0.1‰ in the central part, to more than 1‰ near springs. A vertical gradient is almost nonexistent except near the outlets. DB spring mainly consists of water discharging from the K2Bs aquifer. Water from the K2Ss1 aquifer preferentially flows toward the ZB springs.

Water of the upper K2Bs aquifer of the Zuunbayan sub-basin flows toward the central depression with an average hydraulic gradient of 0.2‰. The K2Ss2 aquifer has an average gradient twice lower which is consistent with the piezometric network observations. However, the computed flow direction of this aquifer appears different than the one presented in Fig. 3. In the model, water is coming from all sides of the sub-basin except from the east, which subsequently becomes the constrained location of the ascending flow. In Fig. 3, flow is directed toward the center of the basin. This difference between observed and simulated piezometric maps may suggest a preferential zone of connection between the two aquifers in the center of the basin. Simulations with a locally removed clay layer were tested but the results did not bring any improvement. It is therefore thought that the shape of this piezometric low may also results from heterogeneity in hydraulic conductivity or a possible connection with another basin to the east.

Conclusions

The conceptualization of the Tsagaan Els basin and the associated groundwater model presented here give a solid basis for any local future hydrogeological studies. This endorheic basin has the particularity to be subdivided into two sub-basins by the North Zuunbayan fault which acts as a flow barrier. Both sub-basins are however interconnected through surface flow transfers from springs located along this fault. The central depression located in the Zuunbayan sub-basin is the terminal discharge playa of the basin while the one in the Unegt sub-basin is only a through flow playa. A 3D groundwater model has been developed based on this conceptualization to further study the Upper Cretaceous aquifer system of this basin. The model has been calibrated with the current piezometric levels only, as surface-water flow is either nonexistent or impossible to gauge. Multiple solutions were found with hydrodynamic parameters consistent with those measured on the field as well as recharge rates, estimated between 0.6 and 3.1 mm/year, consistent with the current climate. Recharge has been supposed uniform on each sub-basin and future development should therefore focus first on the spatialization of this parameter. Nevertheless, the simulated preliminary regional water budget already shows that a minimum of 6.9 Mm^3 of water enters the system annually. This amount is sufficient for the current societal and industrial needs at a regional scale. Water supply in this area may therefore be more constrained by the qualitative aspect of this mostly brackish water resource. Hydrochemical studies have already been conducted in the basin and the results will be highlighted in the near future.

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