The sustainable use of groundwater resources concerning further climate change scenarios in Ulaanbaatar City Area, Mongolia

Dorjsuren Dechinlkhundev, Munkhtsetseg Zorigt and Ijiltsetseg Dorjsuren

ABSTRACT

To estimate groundwater resources under changing climate is one of the important issues for Ulaanbaatar City in the Tuul river basin of Mongolia. The main water supply is provided from groundwater and demand has been increasing due to the rapid growth of population and economic development. There have not been any complete studies to assess climate change impact on groundwater resources for Ulaanbaatar city. Therefore, in this study we proposed to estimate future potential resources of the groundwater from the main wellfields in the city using the AnAqSim (Analytic Aquifer Simulator) model. The model calibration was performed on 10 wellfields during the reference period from 1960 to 2015. Based on the reliable calibration results for the natural conditions, the impact of climate change on groundwater resources was assessed to use the projected HadCM3 scenario for the periods 2046–2065 and 2080–2099. The results of the study contribute to a water management plan for the city to recommend seasonal abstraction.

Key words | AnAqSim, climate change scenario, groundwater sources, Tuul River, Ulaanbaatar city

HIGHLIGHTS

- AnAqSim is one of the potential tools to assess climate change impact on groundwater resources.
- The groundwater resources for the ten wellfields of the Upper Tuul river basin are reasonably modeled and re-estimated using the AnAqSim.
- The wellfields of the upper and downstream side of the Upper Tuul river will be more sensitive to climate change.

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doi: 10.2166/wcc.2021.327
INTRODUCTION

Sustainable water supply is a crucial aspect of human life (Kristvik et al. 2019). Particularly, the regions where water supply is provided by groundwater will become more important due to climate change (Liuzzo et al. 2018; Ghazavi & Ebrahimi 2018). The potential effects of climate change on groundwater are less known than surface water (Nkhonjera & Dinka 2011), but some studies carried out (Liuzzo et al. 2018; Ouhamdouch et al. 2019) different approaches for assessment of climate change (Meixner et al. 2016; Shrestha et al. 2016; Nicolas et al. 2017; Omar et al. 2019). With increasing air temperature and decreasing precipitation leading to a changing recharge regime (Holman 2005; Taylor et al. 2013; Alam et al. 2018) and risks of water scarcity as the climate changes (Doll 2009; Cuthbert et al. 2013; Guermazi et al. 2019).

In Mongolia, the mean annual air temperature has increased by 2.3 °C since 1940 (MARCC 2009). The highest increase in air temperature was observed in winter periods at 3.6 °C (Batima et al. 2005). Not only local changes but also regional climate models showed that the highest changes occurred in the Central and Eastern parts of Mongolia (Gomboluudev & Natsagdorj 2004). For precipitation change, the trend is heterogeneous but decreasing trends predominated in many regions (Dulamsuren et al. 2010; Natsagdorj & Gomboluudev 2017). Especially in July, the reduction of precipitation and increase in evaporation may affect the surface and groundwater regime (Sato et al. 2007). Once there is evidence of changing climate, groundwater responses need to be assessed in the country to support a better plan for groundwater management in the long term (Green et al. 2011). Specifically, Ulaanbaatar is the capital city of Mongolia which is located in central Asia. Administratively, the city consists of nine districts and covers an area of 4,700 km². The population of Ulaanbaatar city has increased by 55% over the past 15 years (Enkhbat et al. 2019) and it is estimated that 1.4 million people now reside there. In the last 50 years, groundwater for Ulaanbaatar has decreased because of the rapid increase in water consumption as well as water scarcity caused by climate change, environmental degradation, and rapid urbanization (Dalai et al. 2019).

The groundwater system is an invisible phenomenon and there are several ways to assess climate change impact, including the numerical modeling approach (Dragoni & Sukhija 2008). Few studies have attempted to analyze climate change impacts on groundwater resources in Mongolia. Bayasgalan et al. (2009) recommended that further climate change is affecting water resources and there is a need to improve the management and groundwater use availability for rural herders. Moreover, Hasiniana et al. (2010) developed a groundwater vulnerability index using the Drastic model in Eastern Mongolian and it was concluded that it is important.
to take appropriate measures for sustainability of the groundwater resources. In recent studies on groundwater modeling in Mongolia, two computer-based models were applied for estimation, such as Modflow based on the finite difference method (FDM) and unit specific yield \( \text{(Buyankhishig et al. } 2009\text{)}, \) and AnAqSim based analytic element method (AEM) and groundwater pumping test parameters \( \text{(Yihdego \\& Paffard } 2017\text{)}. \) AnAqSim (analytic aquifer simulator) is an analytic element software that simulates groundwater flow. It uses subdomains described in Fitts \( \text{(2010), which gives it strong capabilities concerning heterogeneity and anisotropy. However, it uses some approximation for flow between aquifers and applies a radial basis function to estimate groundwater storage } \text{(Bakker } 2013\text{). Some studies suggested AnAqSim as a reasonable tool to model groundwater flow} \text{(Hunt et al. } 1998\text{; Omar et al. } 2019\text{) because it employs multi-level aquifer systems and wide-ranging transient flow simulations} \text{(Yihdego \\& Paffard } 2017\text{; Fitts } 2018\text{).}

In this study we applied an AEM-based AnAqSim model to estimate the groundwater resources of 10 wellfields accounting for climate change impacts in the capital city Ulaanbaatar in Mongolia. The potential impacts of climate change on groundwater resources were calibrated using data from the wells of the city’s groundwater sources. Then, projections of how groundwater resources will be affected by climate change scenarios by 2050 and 2080 were produced using the HadCM3 climate model. The results will help decision-makers manage groundwater resources for the future water demand for a surging population, which has increased since the early 1990s and has doubled between 2009 and 2012 \( \text{(Saladyga et al. } 2013\text{; MEGD } 2015\text{a).}

**MATERIALS AND METHODS**

**Study area**

We included 10 wellfields in the Ulaanbaatar city territory along the Tuul River valley (Figure 1). The Ulaanbaatar
The city is located on the alluvial deposits through the Upper part of the Tuul River basin. The Tuul River basin is one of the 29 river basins of Mongolia with a total area of 49,774.3 km² and the length of the river is 704 km (MEGD 2012). The river originates from Khentel Mountain Range and elevation in the Upper Tuul catchment varies between 585 and 3,502 m above sea level. The catchment area covers 9,000 km². Based on the observed data between 1978 and 2015 at the hydrological station in Ulaanbaatar city, the mean annual runoff is 24.5 m³/s. The main composition of the river’s annual runoff is about 69% rainfall, 6% snowmelt, and 25% groundwater (Davaa & Erdenetuya 2005). According to the observation data of Terelj meteorological station located in the upper part of the basin, the mean annual temperature and precipitation are –3.6 °C and 360 mm between 1986 and 2015, respectively. For the Buyant-Ukhaa station, mean annual air temperature and precipitation are –1.9 °C and 245 mm, respectively. The coldest temperature occurs in January at –21.6 °C in Terelj, –25.6 °C in Buyant-Ukhaa, and the warmest air temperature is in July, measured at 13–19 °C in the basin. About 85–90% of annual precipitation falls in the summer period (MEGD 2012). The wellfields are mainly composed of alluvial deposits which include two unconfined layers. According to the isotopic studies, groundwater and surface water interacts on the floodplain (Tsujimura et al. 2013), which is 1.2–4 km wide.

Seven out of 10 wellfields are the main groundwater sources for the city for domestic water use and the rest of them are for industrial use. Most of the wells in the wellfields have been drilled since the 1960s. For model calibration, data from 266 wells over the wellfields between 1960 and 2015 were gathered and supported by previous studies (Table 1).

Method

As conceptualization of the AnAqSim, a base-map of the study area including wells and a boundary of the wellfields was created in GIS. Then, we built an AnAqSim model in a steady state to model the natural conditions of the aquifer. The steady state model allows modeling of the natural aquifer conditions before any pumping discharge scenarios are performed. For the model calibration, static head, hydraulic conductivity, and specific yields were gathered from the observational values from each site (Table 2). Static water levels of all the boreholes in the aquifer were collected upon their construction, and these were used as calibration heads in the steady state model. Aquifer parameters such as hydraulic conductivity were collected from primary and marginal data from the previous studies and our test results for the boreholes in 2014 and 2015. Data from the previous studies collected information of groundwater tables from wells and boreholes drilled in Tuul River valley since the 1960s, especially information regarding Makh Kombinat (WF5) and Uildver wellfields (WF8, WF9, and WF10) obtained from Russian Expedition Reports pre-feasibility and feasibility studies. Data from other reports were used for the wells in the Yarmag and Buyant-Ukhaa wellfields (WF6 and WF7) (PNIIIS 1980, 1987; JICA 1994). Then we

| ID | Static head, m | Hydraulic conductivity, m/d | Yield, L/s |
|----|---------------|----------------------------|------------|
| WF1 | 0.8–3.2       | 52.6–61.1                  | 5.4–33.8   |
| WF2 | 0.4–2.1       | 156.1–402.9                | 0.6–13     |
| WF3 | 0.8–4.7       | 15.7–61.3                  | 3–28       |
| WF4 | 0.1–3.1       | 42.3–85.1                  | 2.5–25     |
| WF5 | 4.7–6.4       | 86.9–110.4                 | 2–17.4     |
| WF6 | 0.6–1.8       | 49–92.1                    | 8–26.6     |
| WF7 | 0.4–0.8       | 40–45.5                    | 7–15.5     |
| WF8 | 1.8–5.6       | 51–79                      | 8–19       |
| WF9 | 1.3–2.7       | 8–77                       | 10–29      |
| WF10| 1.4–6.1       | 20–115                     |            |

Table 1 | Groundwater wellfields used for the study

| Water supply | ID   | Name of the GW wellfields | Average altitude of the wellfields, m.a.s.l |
|--------------|------|---------------------------|--------------------------------------------|
| Domestic     | WF1  | Deed                      | 1413                                       |
|              | WF2  | Gachuurt                  | 1540                                       |
|              | WF3  | Tuv                       | 1304                                       |
|              | WF4  | Uildver                   | 1300                                       |
|              | WF5  | Makh kombinat             | 1266                                       |
|              | WF6  | Yarmag                    | 1258                                       |
|              | WF7  | Nisikh                    | 1258                                       |
|              | WF8  | DTS-2                     | 1274                                       |
| Industrial   | WF9  | DTS-3                     | 1280                                       |
|              | WF10 | DTS-4                     | 1280                                       |
collected research data gathered during the Hydrogeology Thematic Survey in 2014 and 2015.

For estimation of the groundwater resources, the following formula was used based on fundamental hydrogeological elements:

$$Q_c = \frac{F}{C_1} \cdot \frac{H}{C_1} \cdot n$$

where $F$ is the area of the aquifer, m$^2$; $H$ is depth of the aquifer, m; and $n$ is porosity.

After calibration, the aquifer parameters were put into an analytical spreadsheet, coupled with climate change data for 2046–2065 and 2080–2099. The acceptable steady state parameters were used to model changes in the groundwater resources over the given time periods. Following this step, the expected observed drawdown heads were calculated and fed back into a transient version of the model. The resultant head data was used to calculate wellfield drawdown for the future scenarios if the aquifer was to be dewatered to 50% of its original level.

The formula to calculate initial drawdown results 1 m away from the pumping well used Cooper and Jacob’s (1946) equation. An approximation for the Theis equation was developed (Edwards 2011). The Cooper–Jacob equation used here estimates the drawdown for a given well location over time. The equation is given as follows:

$$s = \frac{Q}{4\pi T} \ln \left[ \frac{2.2459}{\frac{T_t}{rS}} \right]$$

where $s$ is drawdown; $Q$ is pumping rate; $T_t$ is transmissivity; $r$ is the radial distance from the pumping well; and $S$ is the storage coefficient.

**Observed climate changes and future scenarios**

Air temperature has increased by 2.71 °C in the last 70 years based on 48 meteorological stations located across
Mongolia (MARCC 2009). In this study, two meteorological stations covered the study area and air temperature and precipitation data are available between 1978 and 2015 (Figure 2). Observations of the air temperature data suggest an increasing trend (MEGD 2015a). In the Tuul River basin, the air temperature increased by 1.3–1.8°C in dry periods (1996–2015) at Buyant-Ukhaa meteorological station (Sukhbaatar et al. 2017). Compared to the same period, air temperature increased by 0.9°C and precipitation decreased by 32% at Terelj meteorological station (Zorigt et al. 2019).

For climate change scenarios, the best model with minimum error from the statistical assessment of the global climate models is HadCM3 for using climate change scenarios for Mongolia (MARCC 2009). Therefore, we selected the climate change scenario of HadCM3 for the periods of 2046–2065 and 2080–2099 to use for this study. According to the HadCM3 A2 scenario, annual air temperature will be increased by 2.7°C in 2050 and 5°C in 2080. Precipitation will rise by 9% in 2050 and 15% in 2080.

**RESULTS AND DISCUSSION**

The groundwater head at every well was obtained from the model results. The contour map of the wellfields was made using simulated groundwater heads (Figure 3).

Also resulting from the ‘steady state mode’ of the model, the head boundary has been further refined to increase the accuracy of the modeled heads to within ±95% of the head difference.

The simulated groundwater heads were compared to the field observed heads at specific well locations (Figure 4). Based on this, the average difference from the modeled head and observed data was around −2.7 m (range head 40 m). Figure 4 shows the plot between the observed and computed aquifer depth of the wells.

Moreover, aquifer area and depth of the wells were calibrated and values of the aquifer properties for the wellfields are illustrated in Table 3.

Using the results of the aquifer properties, the groundwater resources in the wellfields were calculated using the
area and average depth of the aquifer. The results of the total groundwater sources for Ulaanbaatar city through modeling indicated approximately 287,000 m³/day. Confirmed groundwater resources were counted as 346,000 m³/day by previous studies (MEGD 2013b). Modeled groundwater resources are estimated lower than previous studies because the recharge area has decreased due to the construction of WF8, WF9 and WF10 and increased abstraction for recent years. According to the comparison between modeled and observed aquifer properties, the AnAqSim model is acceptable using fewer data from long-term monitoring. Other studies agreed that the accuracy of AnAqSim is reasonable to model groundwater systems such as mining inflow impacts on groundwater (Yihdego & Drury 2016) and three-dimensional fresh and salt flow (Fitts et al. 2014). These studies validated their results with observed values or other simulation outputs.

The simulation of the future climate by 2050 and 2080, according to the HadCM3 model assuming the A2 emission scenario, was projected on the Tuul basin. The results of the estimation and the potential resources for wellfields in the Tuul basin will be slightly decreased by 2050 and in 2080 as a HadCM3 projection (Figure 5).

In particular, the highest reduction of 5–10% from the current resources on the wellfield of the upstream (WF1, WF2 and WF4) and (WF8, WF9 and WF10) of the Tuul valley will be projected less than that of the middle of the valley (Figure 3). The pumping rate is planned according to future scenarios. WF1, WF5, WF7 and WF9 are suitable for summer and autumn, and the pumping rate accounts for about 45% of the total pumping volume. The rest of the pumping volume is suitable for the spring and winter seasons. Wellfields WF2, WF4, WF6 and WF8 are suitable for pumping 30% of the total abstraction during the summer and autumn seasons. Due to the surface and groundwater interaction regime of the Tuul River, groundwater contributes to surface water during the autumn low water period and surface water feeds groundwater in the spring season (Davaa & Erdenetuya 2005; Batnasan 2001).

By deriving the estimated result of this study, we recommended seasonal abstraction considering groundwater conditions. In other words, less abstraction should be used during winter and spring than during summer and autumn periods (Table 4).

This study can be used for further sustainable groundwater abstraction management for water supply. A similar observation by Omar et al. (2013) concluded that AnAqSim is less complicated than FDM in some cases. Furthermore, this study shows that AnAqSim is one of the ways to evaluate climate change impacts on groundwater resources in terms of time and space. It may be necessary to conduct

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**Table 3 | Description of the aquifer properties for the wellfields**

| ID | Area of the aquifer, F, 10⁴ m² | Average depth of the aquifer, H m | Volume of the groundwater deposits, V 10⁹ m³ |
|----|--------------------------------|----------------------------------|-------------------------------------------|
| WF1 | 30.1                            | 21.61                            | 0.6                                      |
| WF2 | 3.6                             | 3.96                             | 0.01                                     |
| WF3 | 25.8                            | 21.44                            | 0.55                                     |
| WF4 | 4.7                             | 19.8                             | 0.09                                     |
| WF5 | 0.6                             | 21.27                            | 0.01                                     |
| WF6 | 3.2                             | 25.68                            | 0.08                                     |
| WF7 | 3.2                             | 19.09                            | 0.06                                     |
| WF8 | 0.4                             | 23.66                            | 0.009                                    |
| WF9 | 9.1                             | 34.0                             | 0.3                                      |
| WF10| 7.6                             | 43.17                            | 0.3                                      |

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**Figure 4 | Observed and computed aquifer depth for the boreholes.**
further studies to focus the recharge estimation from the precipitation for the well fields. Generally, AnAqSim gives an adequate understanding of the hydrogeological properties of the system using the observational data.

This study can be very helpful for groundwater professionals, policymakers, and city planners in deciding water security and sustainable groundwater use issues of the capital city of Ulaanbaatar, Mongolia.

CONCLUSIONS

The climate change impact on groundwater resources in the seven wellfields for drinking water supply and three wellfields for industrial use in the Upper Tuul basin over the Ulaanbaatar city was assessed using the AnAqSim modeling approach. The aquifer properties and potential groundwater resources of the wellfields were estimated. For this purpose, the area, average depth, and storage of the aquifer in the wellfields were calibrated based on the observational data. The results show that the difference between the observed head and the simulated head is found to be in the 90% confidence level.

The average annual air temperature and precipitation were projected by HadCM3 with an increase of 1–5 °C and 2–15%, respectively, by the end of the 21st century. Potential resources will be decreased by 0.3–10.3 and 1.2–14.8% for 2050 and 2080, respectively. In particular, the wellfields of the upper and downstream side of the river will be more sensitive to climate change. This means we should consider
proper groundwater use plans in the future to maintain sustainable use and for the ecosystem’s wellbeing.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 19 November 2020; accepted in revised form 11 January 2021. Available online 8 March 2021.