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Original Article

Calculation of Potential Groundwater Resources in Orkhon River Basin

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ABSTRACT

Available groundwater research work and data levels are very limited due to the wide territory of our country. Potential Groundwater resources need to be calculated by basin to implement Integrated Water Resources Management Plans. For this purpose, previously the calculations were done twice in the Orkhon River Basin. The last calculation was done 10 years ago, therefore Integrated Water Resources Management Plan needs to be redeveloped, using updated research work and data levels. The Orkhon River is one of the biggest rivers in Mongolia, rising from Khangai Mountain Range and flowing into the Selenge River. The Orkhon River Basin includes the Tuul, Kharaa, and Yeruu rivers basins which rise in the Khentii Mountains. For the first time, a hydrogeological structure map of the basin was developed which analyzed and systemized the hydrogeological structure, the morphostructure factors, and the hydraulic properties of the hydrogeological formations distributed in the Orkhon River Basin. There are two types of hydrogeological basins and three types of hydrogeological massifs in the basin. This paper presents the calculation of the Potential Groundwater Resources (PGR) in the Orkhon River Basin based on groundwater well data, reports of groundwater exploration and research works, and the hydrogeological maps at a scale of 1:500,000. As a result of this calculation, there are 1.99 km^3 of PGR in this basin. The largest resources are found in the linear intermountain hydrogeological basin which occupies 98 percent of the total PGR. Further improvement of the quality and standards of water research remains an important issue for hydrogeologists today.

Keywords: *Hydrogeological massif, Hydrogeological basin, Fault*

INTRODUCTION

Water resource management has become a vital issue, especially in arid and semi-arid regions (Hillel and Jadambaa, 2013; Tuinhof and Buyankhishig, 2010). Mongolia is a country with continental semi-arid climate with low precipitation and temperature fluctuations are high (Nyamtseren et al., 2018). Hence, there is an important need to assess the groundwater resources of the country and the evaluation of the groundwater resources is used for the Integrated Water Resources Management and Planning (IWRMP). There are 2 types of groundwater resources classified as Potential Groundwater Resources (PGR) and Exploitable Groundwater Resources (EGR). The PGR is the total resources that may be abstracted from the groundwater resources. To calculate the PGR of the basin as a source of water supply, it was important to analyze the hydrogeological structure and identify the origin, structure, and accumulation patterns of the aquifer. The estimate of the EGR takes into account the local physical conditions under which groundwater can be abstracted (Jadambaa and Batjargal, 2012a).

The PGR of Mongolia was calculated at about 10,790 million cubic meters in 2003 (Jadambaa and Tserenjav, 2009). Furthermore, the PGR of Mongolia was estimated to be about 10,011 million cubic meters in 2012 (Jadambaa and Batjargal, 2012a). Recently, Dechinlkhundev et al. 2021 estimated the groundwater resources in the upper part of the Tuul River basin under climate change scenarios and concluded that PGR will be decreased by 0.3–14.8% in the future. As part of “The general scheme on integrated use and protection of water resources of the Selenge River Basin”, carried out by the Institute of Water Research and Design (IWRD) was estimated the PGR of the Selenge River and its tributaries, as well as the Orkhon River Basin (IWRD, 1986). The total PGR of the Orkhon River Basin, based on the Hydrogeological Map of Mongolia at scale 1: 1,500,000, calculated in 1986 was 2.3 km^3/year. “Strengthening Integrated Water Resources Management in Mongolia” project estimated the PGR in 2012 for Orkhon and Tuul River basin (Jadambaa and Batjargal, 2012b, c). Based on the Hydrogeological Map of Mongolia at the scale of 1:1,000,000, the PGR was 1.90 km^3/year for Orkhon River Basin. The IWRMP of Orkhon River Basin was completed in 2021, while the last calculation of PGR has already passed 10 years.

To conduct IWRMP, it was necessary to estimate the water resources distributed in any river basin. Estimating and mapping PGR in the Orkhon River Basin has economic and practical implications. For instance, it can be used for the IWRMP and socio-economic development plans, and the maps show the location of specific areas of the PGR. Furthermore, it is impossible to correctly explain any geological process or phenomenon without knowing the function of water in the earth's crust. As well as, V.M. Stepanov emphasizes that, it is impossible to draw the right conclusions about the origin of groundwater without analyzing the geological structure of the region (Stepanov, 1989). Therefore, in hydrogeological research, it is not possible to systematize the hydrogeological structure without analyzing it, first of all, because of the conditions under which rock hydraulic properties are formed, which change under the influence of natural and man-made factors, and the infiltration parameters of water-bearing rocks vary with the geological process.

In this research work, for the first time in the Orkhon River Basin, the main hydrogeological structures were analyzed and the PGR was assessed by classifying the hydraulic properties of rocks.

METHODS AND MATERIALS

Study area

The Orkhon River, the longest river (1124 km) in Mongolia rises from the Khangai Mountain Range and flows into the Selenge River located in the central and northern parts of Mongolia. The study area, the Orkhon River Basin, covers a total area of 143,000 km^2 and it consists of some of the territories of nine provinces and the capital city Ulaanbaatar. The eastern and southwestern part of the study area is mountainous, with an elevation of 2000–3540 m, whereas the northern and central part of the study area consists of low-elevation plains (Fig. 1). In the Orkhon River Basin, the annual average temperature is approximately at -0.7°C, and the average maximum and minimum temperatures are 18.9°C and -24.9°C, respectively, showing the high difference between summer and winter temperatures. The annual average precipitation is 297.6 mm, and 85-90% of the annual precipitation falls in summer (Khishigsuren and Tsogzolmaa, 2012). The primary tributaries of the Orkhon River are the Tuul, Kharaa, and Yeruu rivers all of which rise in the Khentii Mountains (Jadambaa, 2014; Jadambaa 2018). The long-term average runoff of the Orkhon River at Kharkhorin’s gauge is 13.2 m^3/sec and at Sukhbaatar’s gauge is 124.5 m^3/sec (Davaa, 2015). The land use of the Orkhon River Basin is predominantly agricultural, with livestock and herders. Almost half of the population of Mongolia lives in Ulaanbaatar which locates in this basin, and also mining activities and electro energy factories are

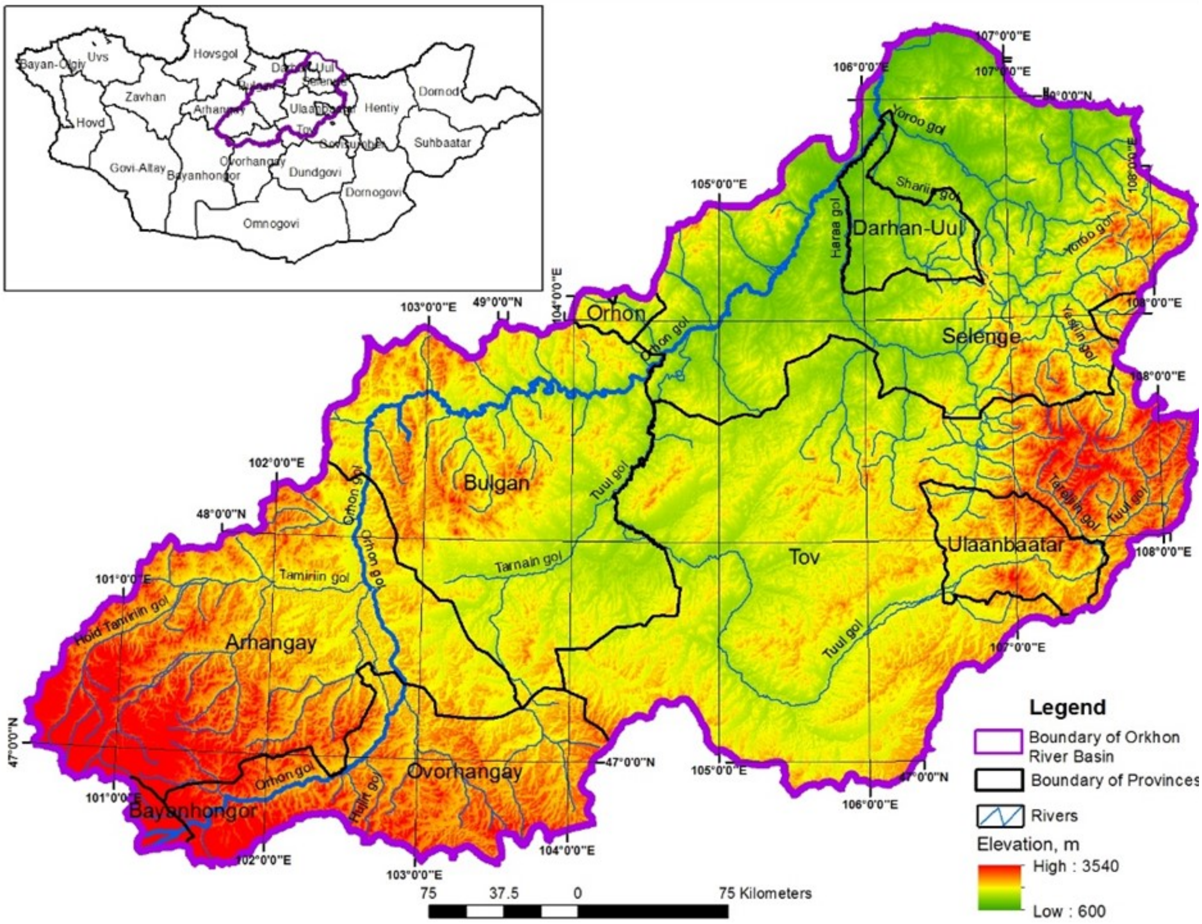

Fig. 1. Location and size of the Orkhon River Basin

influential (Jadambaa and Batjargal, 2012b). In 2020, the total water use of the Orkhon River Basin is 209.8 million m^3/year. The largest water use in the Orkhon River Basin is the agricultural sector (about 40%), followed by drinking water use (approximately 28%), industrial sector use (approximately 26%), and other use (approximately 6%) (Orkhon River Basin Authority, 2020).

Geological and hydrogeological background

Tectonically, the Orkhon River Basin belongs to the Central Mongolian Superterrane and the Khangai-Khentii zone. The Orkhon River Basin is located across the Oortsog-Khuvsgul and Khulj-Yeruu terranes of the Central Mongolian Superterrane and the Tsetserleg, Kharkhorin, Ulaanbaatar, Asralt Khairkhan, and Zag-Kharaa terranes of Khangai-Khentii zone (Fig. 2). The geological structure of the Orkhon River Basin is a unique geological-structural setting, and the current shape is due to multiple geological, structural and tectonic activities during its geological history (Tomurtogoo, 2002). Paleozoic metamorphic rocks, Neogene-Quaternary basalts, and Paleozoic, Mesozoic effusive and intrusive rocks, Permian, Triassic, Jurassic sedimentary rocks, Neogene and lower Cretaceous continental, lake-continental sediments, and Quaternary alluvial, proluvial, deluvial sediments are distributed widely in the Orkhon River Basin. The main structural tendency of the study area is represented by different oriented fault systems and rocks of various ages, dissimilar shapes, and sizes (Jadambaa, 2009).

There are 5 intergranular aquifers (Holocene alluvial aquifer, Pleistocene proluvial, and alluvial-proluvial aquifers, Holocene-Pleistocene proluvial-alluvial aquifers, Neogene

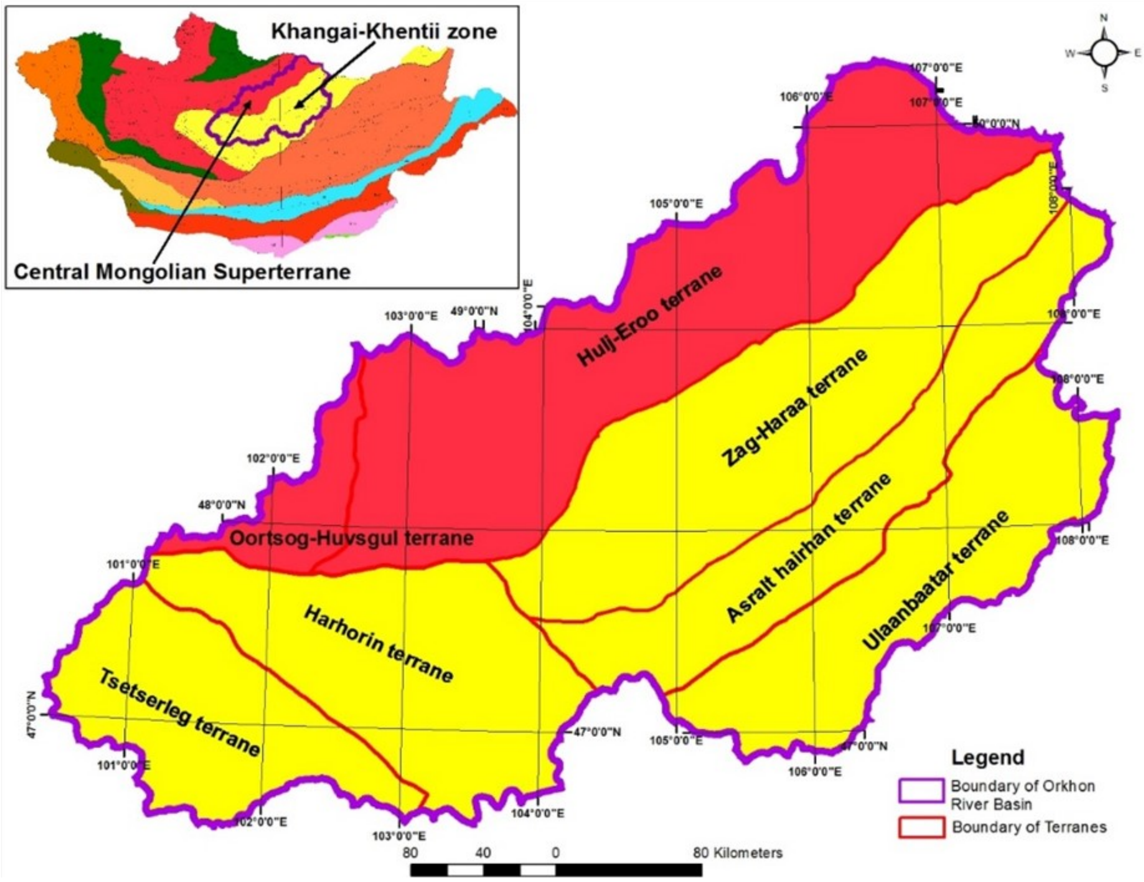

Fig. 2. Tectonic zonation of Territory of Mongolia (Tomurtogoo, 2002)

aquifers, and Cretaceous aquifer) and 2 fissured aquifers (Fissured aquifers in sedimentary, metamorphic and effusive rocks and Fissured aquifers in intrusive rock) in the Orkhon River Basin (Batjargal, 2017; Jadambaa and Batjargal, 2012b). The alluvial aquifer is a water-bearing assemblage of gravels and sands located along the Orkhon River valley and its tributaries. The alluvial aquifer thickness of the Orkhon River (near Sukhbaatar city) ranges from 50 m to 100 m (Vrba, 2013). The proluvial and alluvial-proluvial aquifers are slightly confined, their thickness varies between 19.5-65 m and they are dominantly formed from bank gravel, sand, sandy loam, and mild clay (Jadambaa and Batjargal, 2012c). The Holocene-Pleistocene proluvial-alluvial aquifers consist of different types of sand gravel with boulder and clay and the thickness ranges from 1 m to 54 m. Neogene aquifers are usually confined and consist of sand, conglomerate clay, sandy loam, clay adhesively with coarse gravel, and sand within mild clay. Cretaceous aquifers consist of conglomerate, sandstone, argillite, siltstone, coal, clay, and sand. The distribution of the Neogene and Cretaceous aquifers is very limited in the Orkhon River Basin and the thickness of these aquifers is 1-20 m (Jadambaa et al., 2017).

Fissured aquifers in sedimentary rocks of Triassic-Jurassic-Permian consist of conglomerate, sandstone, argillite, siltstone, shale, coal, gravels, and boulders while fissured aquifers in sedimentary-metamorphic, metamorphic, sedimentary-effusive and effusive rocks of Paleozoic consist of shale, sandstone, dacite porphyry, rhyolite porphyry, porous and solid dense basalts, andesitic basalts, andesitic dacite, trachyandesite, gneiss, and dolomite. These aquifers have a broad distribution in the Orkhon River Basin, but water resources are low and the thickness is 1-21 m. The fissured aquifer in intrusive rock is widely distributed in the Orkhon River Basin and the water quantity is not high. The water quality is good in most cases, so local people use it for water supply by drilling wells. The aquifer thickness is 3-100 m (Jadambaa and Batjargal, 2012b, c).

A hydrogeological structure analysis and the PGR calculation

Cartography and regional groundwater system analysis methods were used in the study. First, a hydrogeological structure map of the study area was developed by classification of Stepanov (Stepanov, 1989) using morphostructure factors, the hydraulic properties of the water-bearing rock formations, and the hydrogeological maps at a scale of 1: 500,000 (Jadambaa et al., 2017). Second, the PGR calculation was based on the hydrogeological structures map, previous reports of groundwater exploration surveys, and used groundwater well data. The groundwater well data were collected from the database of the Institute of Geography and Geoecology and reports of the Water Authority.

The PGR is calculated using the balance method (Bindeman and Yazvin, 1970; Drobnokhod, 1976). In this case, the hypothetical abstraction wells were placed in the same sized grid applied on the distribution area of the hydrogeological structures. The grid size is 5 km x 5 km and a total of 5,440 hypothetical abstraction wells were used in the study area (Fig. 3). Each grid cell area is 25 km^2. Assuming that boundary conditions of the grid cells are no flow and groundwater recharge was not considered. This calculation will enable a more realistic IWRMP because the calculation uses the groundwater resources which are already stored in the hydrogeological structure. If there is no groundwater well data in the grid cell, PGR was estimated using the data of the adjacent grid cell with groundwater well data. PGR is calculated using the following equations (Bindeman and Yazvin, 1970; Drobnokhod, 1976; Battumur, 2015):

For the unconfined aquifer:

$$Q_{PGR} = \mu \frac{S}{t_T} F \qquad (1)$$

where μ -is the specific yield, ***S*** -is the potential drawdown [m], t_T -is the operating period of water use [25 years], ***F*** -is the aquifer distribution area [m^2], h is the aquifer thickness [m].

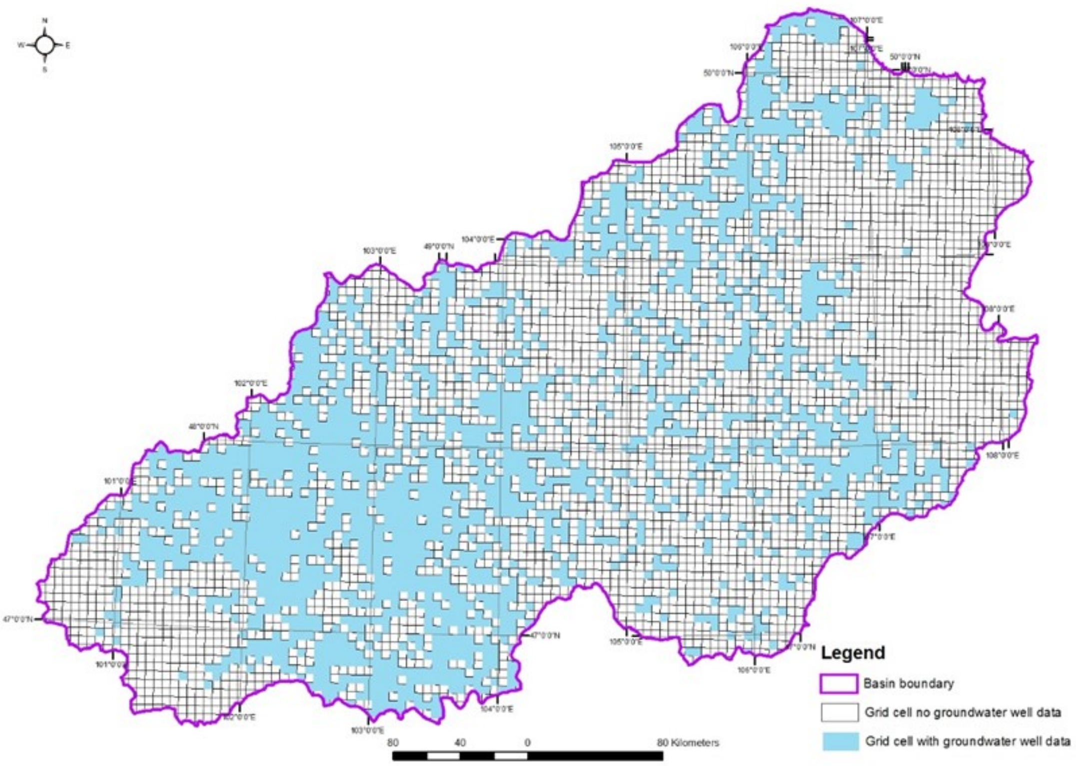

Fig. 3. The grid cell with/no groundwater well data for the Orkhon River Basin

For the confined aquifer:

$$Q_{PGR} = [\mu^* H' + \mu^*(S - H')]\frac{F}{t_T} \qquad (2)$$

where μ* -is the storage coefficient, ***H'*** -is the pressure head [m], ***S*** -is the potential drawdown [m], t_T -is the operating period of water use [25 years], ***F*** -is the aquifer distribution area [m^2], h is the aquifer thickness [m]. According to the regulation for the calculation of PGR, the potential drawdown is ***S=0.5·h*** (50% of aquifer thickness) for unconfined aquifer and ***S=H'+0.5·h*** (pressure head + 50% of aquifer thickness) for the confined aquifer.

The PGR map was developed using the overlapped hydrogeological structure map and the result of the PGR calculation in each grid cell. There are 7 categories for the classification of the PGR map using ArcGIS version 10.2 (ESRI, Inc., Redlands, Ca, USA).

RESULTS

In terms of hydrogeological structure, there are three main types of structures are classified in the Orkhon River Basin: 1) orogenic hydrogeological massifs, 2) intermountain hydrogeological basins, and 3) water-bearing faults (Fig. 4). These main types of hydrogeological structures can be subdivided into 3 types of hydrogeological massifs, 2 types of hydrogeological basins, and 2 types of faults according to the classification of Stepanov (Stepanov, 1989).

The orogenic hydrogeological massifs

These orogenic hydrogeological massifs are distributed in 68 percent of the study area and the massifs are classified as Block-structured orogenic crystalline hydrogeological massif, Overflowed and covered orogenic structured volcanic hydrogeological massif, and Block-

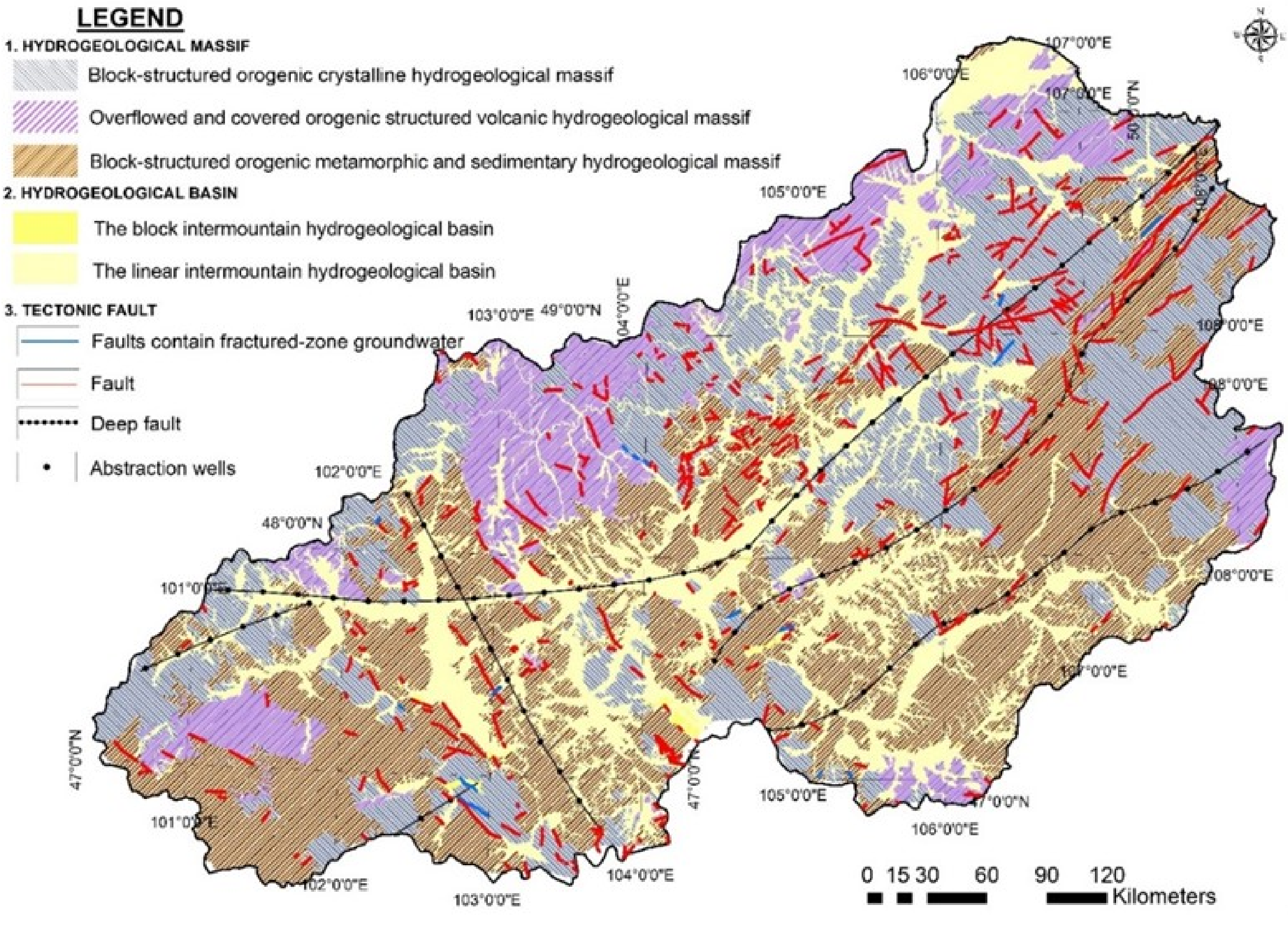

Fig. 4. The hydrogeological structure map of the Orkhon River Basin

structured orogenic metamorphic and sedimentary hydrogeological massif. The massifs weathered zones are characterized by hydraulic properties of rocks as a fissured porous medium and fissured medium. Zaparii (1963) noted that fractured zones of the massifs in the Mongolian Arid Zones can hold the groundwater at various depths, 100-120 m in metamorphic and sedimentary hydrogeological massifs, 100 m in the volcanic hydrogeological massif, and 60-80 m in the crystalline hydrogeological massif.

Block-structured orogenic crystalline hydrogeological massif is intrusive rocks with water-bearing fractures. The intrusive rocks are biotite-amphibole granite gneiss, reddish-pink syenite, quartz syenite, leucocratic granite, diorite, gabbro diorite, and gabbro. This massif is characterized by hydraulic properties as fissured medium and is distributed over 25 percent of the study area (Fig. 4). The groundwater resources of the crystalline hydrogeological massif are larger than that of the Paleozoic metamorphic rocks. Intrusive rocks are widespread in the Orkhon River Basin, but they possess limited groundwater resources. From the data from 150 groundwater wells drilled in this massif, the groundwater level is between 0.7-40 m in depth and the yield is between 0.06-4.0 l/s. The total PGR of the block -structured orogenic crystalline hydrogeological massif is estimated at 7,403.5 thousand m^3/year and 0.002-0.06 l/sec/km^2. The PGR to be used from a hypothetical abstraction well ranges from 1.5-50 thousand m^3/year (Table 1).

Overflowed and covered orogenic structured volcanic hydrogeological massif is mostly distributed in the northern part of the study area belonging to the Khulj-Yeruu terrane of the Central Mongolian Superterrane. The massif is little distributed in the eastern and southwestern part of the study area and belongs to the Ulaanbaatar terrane and Tsetserleg terrane of the Khangai-Khentii zone. The orogenic volcanic hydrogeological massif consists of dacite porphyry, rhyolite porphyry, porous and solid dense basalts, andesitic basalts, their sediments, andesitic dacite, and trachyandesite. The massif is distributed in approximately 9.2 percent of the study area and is characterized by hydraulic properties as a fissured porous medium. The data on yields of groundwater wells drilled in this type of massif is scarce, and very little hydrogeological research has been conducted. The total PGR of the weathered fractured zone of this type of massif is 1,996.5 thousand m^3/year and 0.003-0.02 l/sec/km^2. The PGR to be used from a hypothetical abstraction well in the massifs is 1.5-15 thousand m^3/year (Table 1).

Block-structured orogenic metamorphic and sedimentary hydrogeological massif is widely distributed throughout the Khangai-Khentii zone of the Orkhon River Basin. The yield of groundwater wells drilled in this massif varies between 0.5-25.0 l/s. From the data, the groundwater wells drilled in the Paleozoic metamorphic massif in the northeastern part of Ulaanbaatar city, the groundwater level was found at depths from 13.0 to 40.0 m. Similarly, in the fractured zone of the metamorphic sandstone massif in the northwestern part of Ulaanbaatar city, the groundwater level was found at a depth between 4.7-15.85 m. And data from groundwater wells drilled in Ulaanbaatar's depression zone, the groundwater level was found between 3.7-40.0 m and the yields ranged from 0.07 to 5.6 l/s (Jadambaa and Batjargal, 2012c). This type of massif included Jurassic, Triassic, Permian sandstone, cobblestones, gravel, conglomerate, siltstone, gravellite, shale, and argillite sediments and their aquifers are generally unconfined. The massif is distributed in approximately 33.5 percent of the study area and is characterized by hydraulic properties as a fissured porous medium. The total of PGR from the weathered fractured zone of this type of massif is calculated at 13,984 thousand m^3/year and 0.002-0.1 l/sec/km^2 (Table 1). The PGR to be used from a hypothetical abstraction well in the Paleozoic metamorphic massif is 1.5-15 thousand m^3/year whereas 5-105 thousand m^3/ year for the Jurassic, Triassic, and Permian sedimentary massif.

Intermountain hydrogeological basins

The intermountain hydrogeological basins are distributed in 32 percent of the Orkhon River

Basin, and are divided into two types: 1) Block intermountain hydrogeological basin and 2) Linear intermountain hydrogeological basin.

The block intermountain hydrogeological basin includes Neogene aquifers consisting of mostly red clay, loam, sandstone, conglomerate, gravel, and gravelly sandstone and Cretaceous aquifers consisting of sandstone, conglomerate, cobblestone, gravellite, siltstone, and coal shale sediments formed continental. Neogene and Cretaceous aquifers in this basin are usually confined and are characterized by hydraulic properties as a porous medium. This basin is distributed in a very small area (approximately 1.7 percent) in the study area belonging to the Kharkhorin and Ulaanbaatar terranes of the Khangai-Khentii zone and its water resources are not high. The total PGR of the block intermountain hydrogeological basin is calculated at 1075 thousand m^3/year and 0.006-0.13 l/sec/km^2. The PGR to be used from a hypothetical abstraction well located in Neogene aquifers is 5-100 thousand m^3/year and from a hypothetical abstraction well located in Cretaceous aquifers is 5-25 thousand m^3/year (Table 1).

The linear intermountain hydrogeological basin is located along the whole length of the Orkhon River Basin and its tributary rivers which are distributed in 30.4 percent of the study area. This basin includes Holocene alluvial aquifers, Pleistocene proluvial, and alluvial-proluvial aquifers, and Holocene-Pleistocene proluvial-alluvial aquifers, it is characterized by hydraulic properties as a porous medium. The aquifers of this hydrogeological basin are with a high storage coefficient and hydraulic conductivity. Thus, the total PGR of this hydrogeological basin is calculated at 1,962,488.0 thousand m^3/year and 0.2-15.98 l/sec/km^2. The PGR to be used from a hypothetical abstraction well is 150-12,600.0 thousand m^3/year (Table 1).

Water bearing faults

The orogenic hydrogeological massifs are widely intercepted by various tectonic faults. These faults are classified as deep and shallow according to the classification of the hydrogeological structure (Stepanov, 1989). The deep faults contain no water while the shallow faults may contain groundwater (Fig. 4). However, the water-bearing faults in the Orkhon River Basin have been poorly studied (Jadambaa, 2009; Jadambaa and Batjargal, 2012c).

Based on the Hydrogeological structure map and the result of the PGR, the potential groundwater resources per 1 square km are divided into 7 classifications which are shown in Fig. 4. The high value is more than 10 l/sec/km^2 and belongs to the Tuul, Kharaa, and Yeruu Rivers valleys where detailed hydrogeological exploration surveys have been done. The very

Table 1. The PGR in different types of the hydrogeological structures

№	Hydrogeological structure	Resources, l/s*km^2	Percentage of total area	Total resources, 10^3*m^3/year
1	The block-structured orogenic crystalline hydrogeo-logical massif	0.002-0.06	25	7,403.50
2	The orogenic structured volcanic hydrogeological massif	0.003-0.02	9.2	1,996.50
3	The orogenic metamorphic and sedimentary hydro-geological massif	0.002-0.1	33.5	13,984.00
4	The block intermountain hydrogeological basin	0.006-0.13	1.7	1,075.00
5	The linear intermountain hydrogeological basin	0.2-15.9	30.4	1,962,488.00
			Total	**1,986,947.00**

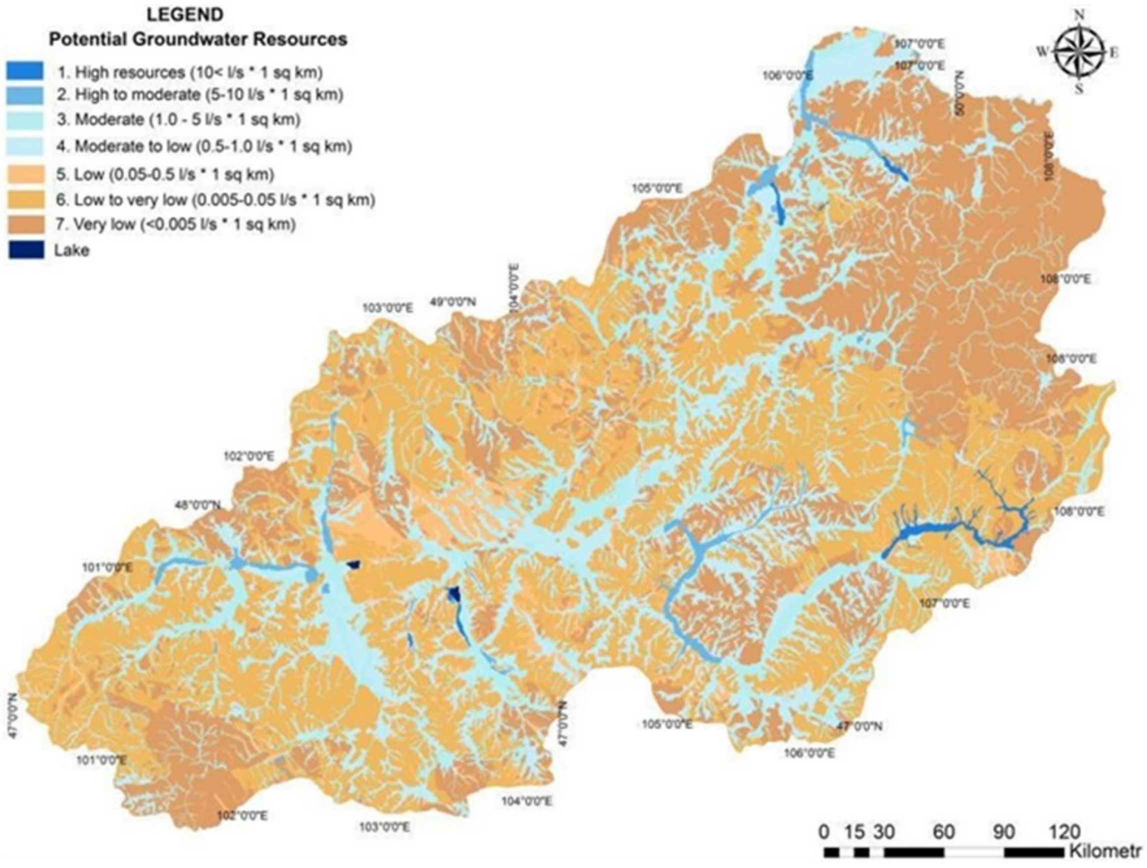

Fig. 5. The potential groundwater resources map of the Orkhon River Basin

low value is less than 0.005 l/sec/km^2, it may be related to few groundwater well data and low storage coefficient of aquifers in the orogenic hydrogeological massifs.

DISCUSSION

The calculation of the PGR, which is more than 90 percent of the source of water use, is important for the planning and implementation of water resource management in the Orkhon River Basin. Resource estimation provides the basis for the management and planning of groundwater use in the basin. Previously, the general scheme for integrated use and protection of water resources of the Selenge River Basin in 1986 calculated the PGR using a 1:1,500,000 scale hydrogeological map and other survey data available at the time. While the Strengthening Integrated Water Resources Management in Mongolia project in 2012 estimated the PGR using a 1:1,000,000 scale hydrogeological map, and hydrogeological surveys up to 2012.

Ten years have already passed since the last calculation and it is reasonable to assume that more accurate estimates are possible of the PGR using a 1:500,000 scale hydrogeological map developed based on a 1:200,000 scale geological map and the hydrogeological structure map of the Orkhon River Basin. The PGR of the orogenic hydrogeological massifs is low because these massifs are mostly characterized as fissured aquifers, whereas the PGR of the linear intermountain hydrogeological basin is high which may provide the groundwater accumulation zones. The calculation of the PGR did not include recharge but the linear intermountain basins can be recharged from April to October by rivers. Due to the poor quality of registration and collection of data of recent hydrogeological drillings in a separate database, which is not well organized and cannot be used by researchers in the future. This research can be continued in other basins for IWRMP. In addition, the need to integrate the water database and improve the quality and standards of water research is an important issue for hydrogeologists today. Also, it is important to increase groundwater research work and improve the standards and regulations.

CONCLUSION

1. In terms of hydrogeological structure, three main types of structures can be distinguished in the Orkhon River Basin: The orogenic hydrogeological massifs, the intermountain hydrogeological basins and the water-bearing faults.
2. In the fault zones are wells with high yield and springs, but the water bearing-faults are not well studied in this basin.
3. A total of 1,986.9 million m^3/year or 1.99 km^3/year of PGR is estimated in the Orkhon River Basin which is 18.3 percent of the total groundwater resources of Mongolia. About 1.2% of the total PGR is set in the orogenic hydrogeological massifs while approximately 98.8% of the total PGR is set in the intermountain basin.

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