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Analysis of natural water resources formation and distribution conditions in Central Ethiopia

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Abstract. Water is the most important natural resource that ensures Earth's ecological system operation. The variability of the resource potential of the hydrosphere has a significant, if not decisive, impact on the socio-economic development of the world including Ethiopia in general and its central regions in particular where surface water is the main source of water supply. Growing urbanization, industrialization and agricultural development have increased the demand for multipurpose water supply in the agricultural, industrial and energy sectors of Ethiopia. Due to the increased water demand during the dry seasons of the year the country faces severe water shortages, while the amount of surface water during the rainy seasons quite accommodates modern demands. The purpose of this study is to analyze the natural formation and distribution conditions of surface and groundwater resource potential in Central Ethiopia as well as to identify the most promising sites for groundwater prospecting and exploration. Having processed and analyzed the materials using Google Earth Engine cloud technologies and a number of software packages, it was determined that the structural and tectonic development of the territory caused by the region's confinement to the East African Rift Zone, plays a decisive role in the formation of natural conditions both in Ethiopia as a whole and in its central part in the distribution of natural water resources. The relief, climatic features, and main geomorphological and geological structures are the result of past and ongoing tectonic processes. Understanding of surface and groundwater formation and distribution conditions in the region, significant volume of source material, and the use of modern processing means create the basis for a quantitative assessment of surface water resources and the delineation of the most water-abundant areas of the subsoil.

Keywords: Ethiopia, resources, water supply, surface water, groundwater, hydrosphere, natural conditions, structural and tectonic features

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ГЕОЛОГИЯ, ПОИСКИ И РАЗВЕДКА ТВЕРДЫХ ПОЛЕЗНЫХ ИСКОПАЕМЫХ, МИНЕРАГЕНИЯ

Научная статья

УДК 556.33+556.5

Анализ условий формирования и распределения ресурсов природных вод на территории Центральной Эфиопии

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Резюме. Вода – важнейший природный ресурс, обеспечивающий функционирование экологической системы Земли. Изменчивость ресурсного потенциала гидросферы оказывает существенное, если не определяющее, влияние на социально-экономическое развитие мира, включая Эфиопию, особенно ее центральные районы, где основным источником водоснабжения являются поверхностные воды. Растущие урбанизация, индустриализация и развитие сельского хозяйства привели к увеличению спроса на разноцелевое водоснабжение в аграрном секторе, промышленности и энергетике. Из-за возросшего спроса на воду в засушливые сезоны года в стране ощущается острая ее нехватка, в то же время в сезоны дождей количество поверхностных вод вполне удовлетворяет современные



потребности. Цель данного исследования – анализ природных условий формирования и распределения ресурсного потенциала поверхностных и подземных вод Центральной Эфиопии, выявление участков, наиболее перспективных для поисково-разведочных работ на подземные воды. В результате обработки и анализа материалов, которые осуществлялись с использованием облачных технологий Google Earth Engine и ряда программных комплексов, определено, что решающее значение в формировании природных условий как Эфиопии в целом, так и ее центральной части в распределении ресурсов природных вод играет структурно-тектоническое развитие территории, обусловленное приуроченностью региона к Восточно-Африканской рифтовой зоне. Рельеф, климатические особенности, основные геоморфологические и геологические структуры – результат прошедших и продолжающихся тектонических процессов. Понимание условий формирования и распределения поверхностных и подземных вод региона, значительный объем исходного материала, использование современных средств его обработки являются базой для количественной оценки ресурсов поверхностных вод и оконтуривания наиболее водообильных участков недр.

Ключевые слова: Эфиопия, ресурсы, водоснабжение, поверхностные воды, подземные воды, гидросфера, природные условия, структурно-тектонические особенности

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Introduction

Water is a limited natural resource [1–4]. The variability of this resource has largely determine the functioning of the Earth's ecological system and the development of the social and economic structures of the world, including Ethiopia, especially its central regions. The intensity of urbanization [5] and a sharp increase in the world's population [6], the deterioration of the environmental situation, significant water losses in industry and utilities [7], as well as the irrational use of natural water, led to a noticeable reduction in water resources [8].

Due to the growing demand for water in Ethiopia, there is an acute shortage of water during the dry periods of the year, while excess surface water occurs during the rainy season, which fully meets existing needs. Pollution also exacerbates a region's water scarcity by making water unfit for different uses and reducing freshwater availability and local water scarcity may lead to economic output losses, and the risk can be transmitted to downstream sectors through reduced input supplies [9–11].

Global climate change affects the intensity of precipitation [12], infiltration [13] and evapotranspiration [14, 15]. These changes affect the rivers water abundance and the recharge of aquifers [16–18], which are used for water supply and determine the availability of water resources [16, 19, 20]. The uneven distribution of water within the country plays a major role, which further increases the economic consequences of water scarcity. Thus, assessing the spatial structure of water scarcity is very important for reducing economic risks in various economic sectors.

These reasons necessitate a detailed analysis of the natural conditions for the formation

and long-term monitoring of the water resources in Central Ethiopia, which is necessary for decision-making regarding the management of water resource potential and the development of a structure for its use for sustainable economic development of the region.

This study aims to reveal the natural conditions for the formation and distribution of surface and groundwater resource potential in Central parts of Ethiopia and to identify areas most promising for prospecting and exploration of groundwater for multipurpose water supply.

To achieve this goal, the following tasks are investigate:

- analysis of surface and groundwater natural conditions for the formation of in Central Ethiopia;
- characteristics of spatial and temporal variability of the hydrodynamic regime of the surface and groundwater resource potential in Central Ethiopia;
- identification of the main factors influencing the spatial and temporal dynamics of the natural water resource potential.

Materials and methods

The study area is located in the central part of Ethiopia in the zone of influence of one of the largest spreading structures – the East African Rift System.

The analysis for the conditions of distribution and formation of natural water resources is based on a large volume of heterogeneous datasets, including long-term precipitation and temperature data obtained at the Ethiopian Meteorological Institute; geological and structural-tectonic maps provided by the Ministry of Mines and Petroleum of Ethiopia; information on groundwater intake wells obtained from the Ministry of Energy and



Ethiopia's water resources, etc. In addition, remote sensing data was used in this study, including digital terrain models, lineament density, and other materials. The total volume of the database was 1,500 observation well points, characterized by 34 indicators. The materials were analyzed using Google Earth Engine cloud technologies and a number of software packages, including PCI Geomatica, R-Studio, and ArcGIS 10.4.

Results and discussion

The most significant influence on the formation of Ethiopia's natural conditions, including water resources, as in other similar regions [21, 22], was exerted by the structural and tectonic development of the territory, due to its proximity to the East African Rift zone. Ethiopia is located at the junction of three lithospheric plates: Nubian, Arabian and Somali (Fig. 1). As a result of the developing rifting process, a number of elongated low-lying valleys were formed, bounded by steeply falling normal faults and separated by raised blocks. The Nubian and Somali plates separate

from the Arabian Plate in the north, thus creating a Y-shaped rifting system. These plates intersect in the Afar region of Ethiopia in an area known as the "triple junction", where the formation of an active continental rift zone begins, extending further south and began developing in the Miocene [23].

The main factors influencing the formation of surface and groundwater resources were identified: relief, density of the river network and steepness of the slopes, climatic characteristics (precipitation, temperature, evapotranspiration, etc.), structural-tectonic and geological-hydrogeological features of the territory.

The topography of Ethiopia is one of the most rugged and complex in Africa and is divided into five topographic units: the Main Rift Valley, the Western Lowland, the Western Highlands, the Eastern Lowlands and the Eastern Highlands. In general, the position of the territory of Ethiopia above sea level ranges from -48 m (at the sides of volcanic structures in the Denakil depression, the mark of the bottom of the volcano of the same name is -214 m) to 4620 m (Ras Dashen Mountain). In the central

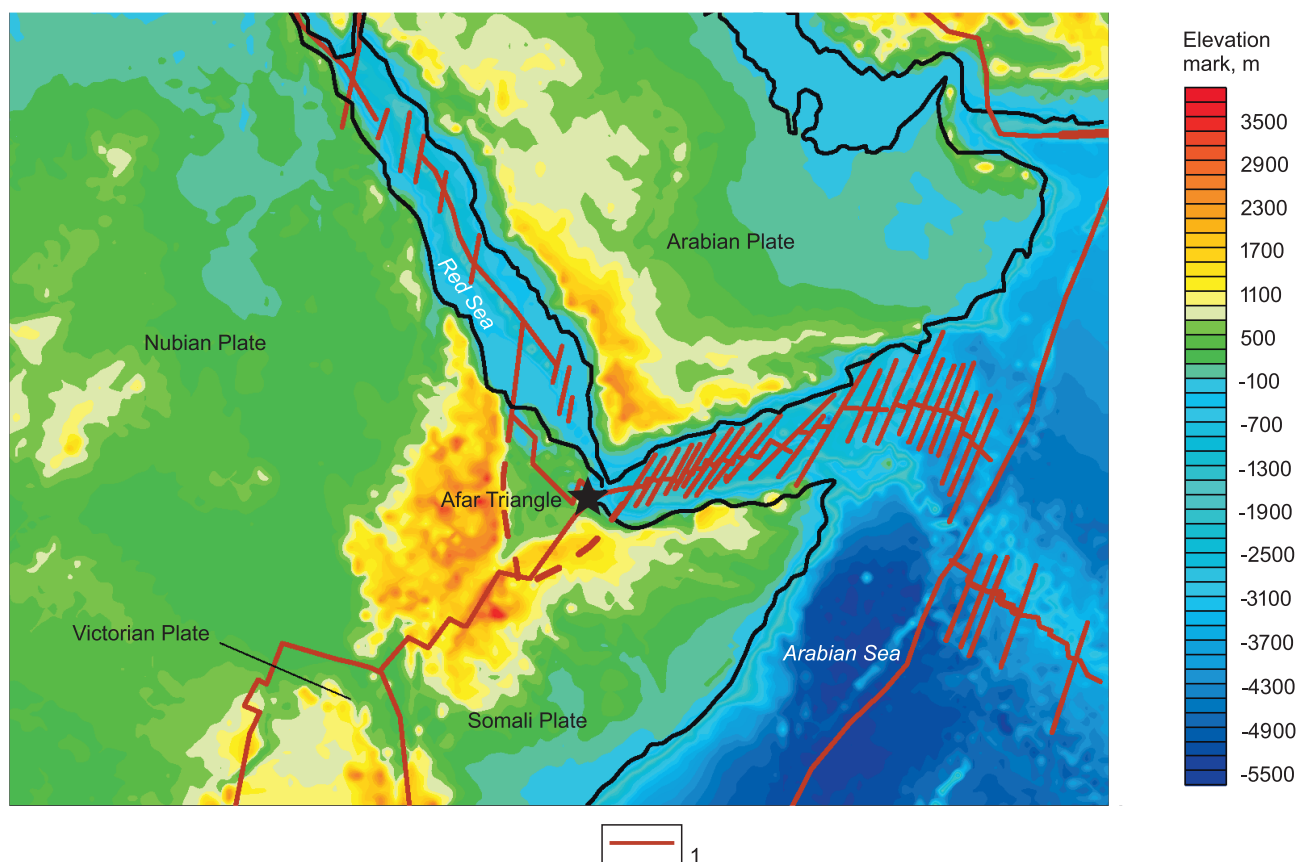


Fig. 1. Overview map of main tectonic element location in the region (a fragment) (according to the source [23] with authors' translation):

1 – faults

Рис. 1. Обзорная карта расположения основных тектонических элементов региона (фрагмент) (согласно источнику [23] с переводом авторов):

1 – разломы



part, the absolute elevation ranges from 74 m (Afar Valley) to 4266 m (Choki Mountain) (Fig. 2).

The sharply dissected relief plays a significant role in the formation of water resources, since at high altitudes there is an accelerated flow of water from the upper to the lower sections of the slope, which increases the surface runoff in accordance with the hydraulic slope, on more gentle slopes the volume of surface runoff decreases, which allows more precipitation to penetrate into the earth's crust through zones of exogenous and tectonic fracturing [24]. In addition, the steepness of the slopes significantly affects the infiltration rate and distribution of water among various geomorphological elements [25, 26]. For example, studies conducted in Taiwan prove that there is a significant correlation between changes in absolute altitudes and groundwater levels [26, 27]. Thus, taking into account topographic features when considering the conditions for the formation of natural water resources is necessary and fully justified.

The variation of Ethiopia's terrain leads to dramatic differences in climatic conditions. The country's territory is located in the equatorial and sub-equatorial zones. The location of the central part of the country within the Ethiopian Highlands explains the milder and wetter climate in this region. The lowland eastern regions of Ethiopia are the complete opposite: they have a hot and dry desert climate.

The amount of precipitation in the region also fluctuates widely: from 620 to 1200 mm/year. The annual precipitation layer thickness fluctuates from 9.10 to 162.5 mm (Fig. 3). Such significant areal fluctuations are characteristic of the development of the intertropical convergence zone [28]. The maximum amount of precipitation falls in the southern and southwestern parts of the country, where equatorial tropical forests are widespread, and the minimum – in the eastern, northeastern and southeastern parts of Ethiopia (for example, the Ogaden region, the Danakil Desert, etc.).

Seasonal variations in precipitation are an important factor in assessing natural water resources. In Ethiopia, there are three main seasons: the dry Bega season (October to January), the less dry Belg season (February to May), and the rainy Kiremt season (June to September) [29].

Evaporation plays a significant role in the distribution of water resources, especially in natural water bodies such as lakes, rivers, and reservoirs. The amount of evaporation decreases from the southwest to the northeast of Ethiopia from 1600–1800 mm/year to 600–1000 mm/year. Accordingly, the evapotranspiration index changes, taking into account the total amount of moisture entering the atmosphere in the form of steam as a result of transpiration and evaporation from the soil and from the surface of vegetation (Fig. 4). The total evapotrans-

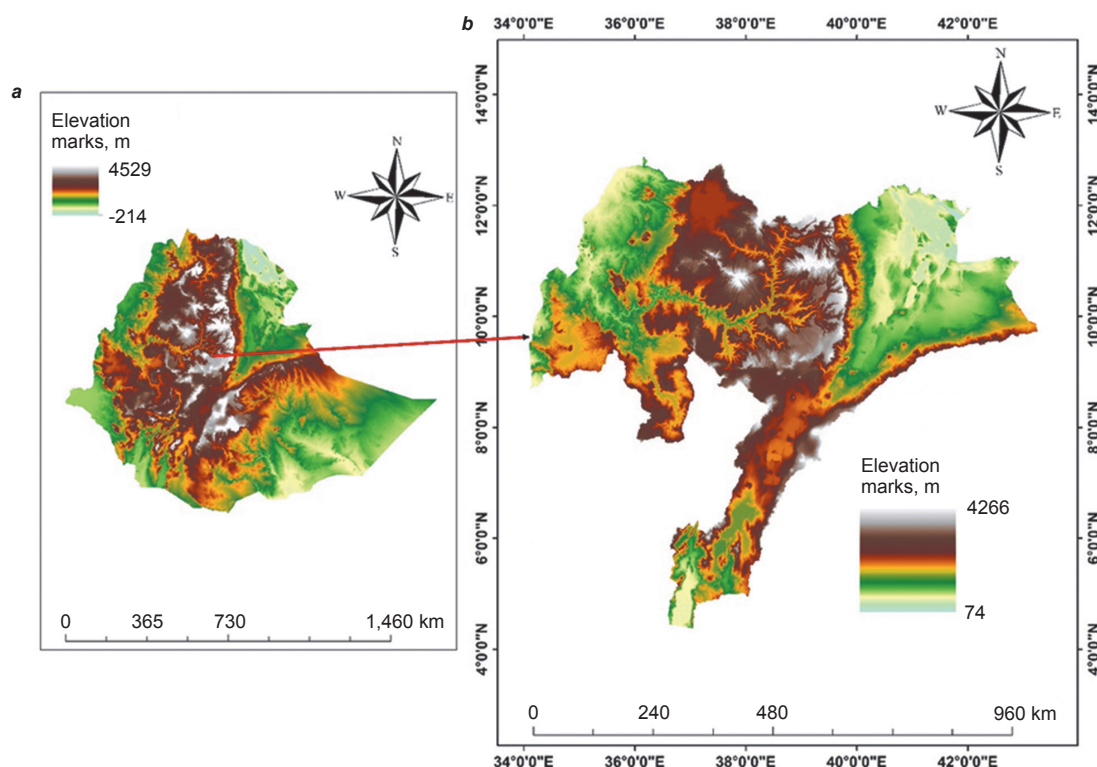


Fig. 2. Digital elevation model of Ethiopia (a) and its central part (b)
Рис. 2. Цифровая модель рельефа Эфиопии (a) и ее центральной части (b)

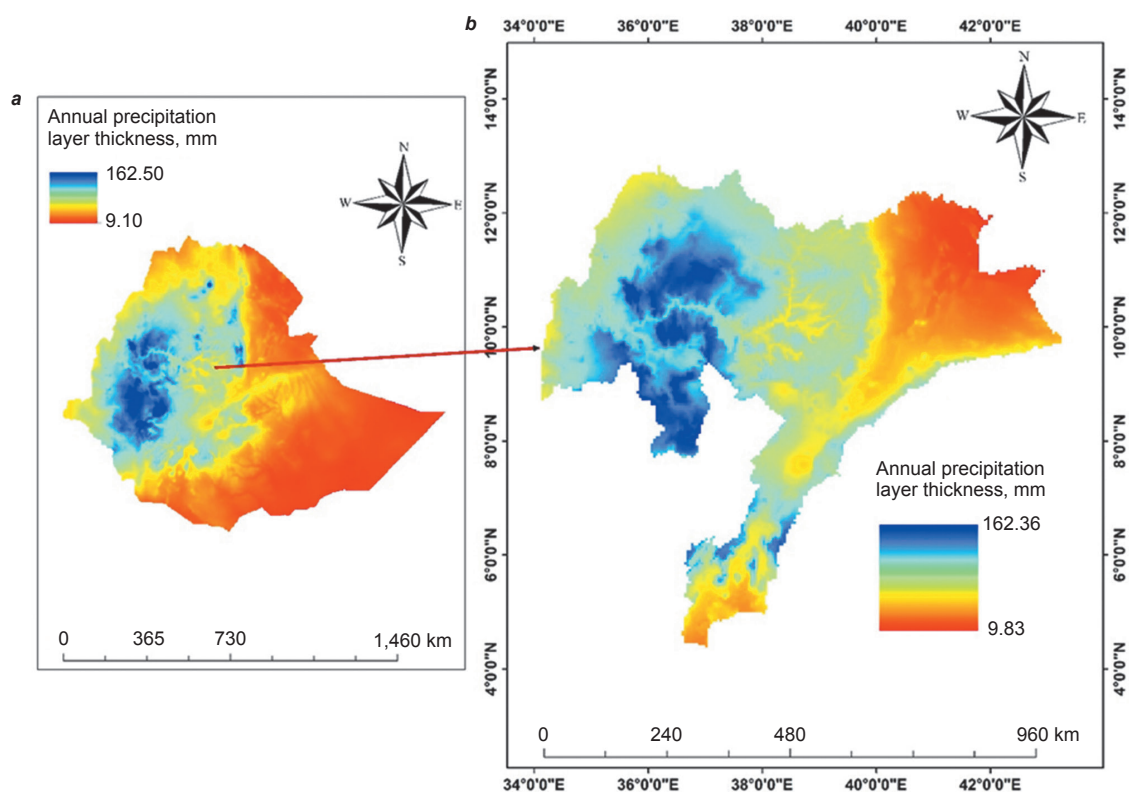


Fig. 3. Distribution of annual precipitation layer thickness on the territory of Ethiopia (a) and in its central part (b)
Рис. 3. Распределение мощности слоя атмосферных осадков на территории Эфиопии (a) и ее центральной части (b)

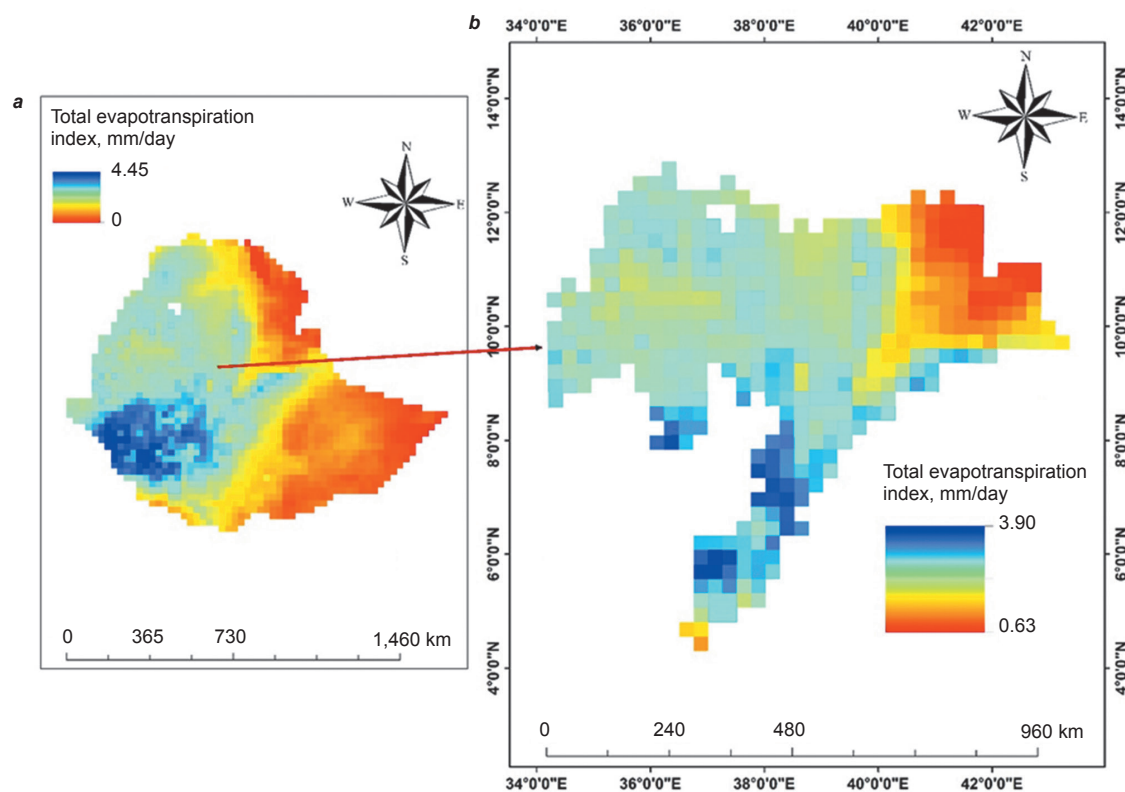


Fig. 4. Distribution of total evapotranspiration on the territory of Ethiopia (a) and in its central part (b)
Рис. 4. Распределение суммарного показателя эвапотранспирации на территории Эфиопии (a) и ее центральной части (b)



piration index depends on the landscape features of the study area, most of which is occupied by agricultural lands and steppes (Fig. 5).

The temperature regime is also one of the most important factors influencing the formation of water resources, since it regulates the evaporation rate and humidity of air and soil. This is especially noticeable in arid and semi-arid regions [30]. The temperature in Ethiopia ranges from 6.6 to 31.5 °C (Fig. 6). May is a hot and dry month preceding the long rainy season in June, July and August. The lowest temperatures are usually observed in December or January, and the hottest in March, April or May. Average annual temperatures in highlands are about 15–20 °C, while in the lowlands it is 25–30 °C. The average annual temperature in Ethiopia from 1901 to 2024 ranged from 22.15 to 23.96 °C. An increase in temperature leads to significant changes in the amount and intensity of precipitation, as well as an increase in water temperature.

Surface water resources used for multi-purpose water supply during periods of precipitation are determined by an extensive river network. Most of the rivers in western Ethiopia belong to the Nile basin. The largest among them is Abbaye or Blue Nile. Ethiopia's largest lake, Lake Tana, is located here in the north of the country, which is the source of the Blue Nile. In the east, the rivers are less full, which is associated with a more arid climate. The largest river is the Juba. A large number of small lakes are located in the Great Rift Valley area. The level of reliability of determining the boundaries of catchment areas plays an essential role in assessing surface water resources [31]. In conditions of very low study of the country's territory, remote sensing data was used to determine the boundaries of river basins, followed by the use of GIS technologies, which made it possible to identify 9 river basins within Ethiopia (Fig. 7): Abbay, Genale, Ogaden,

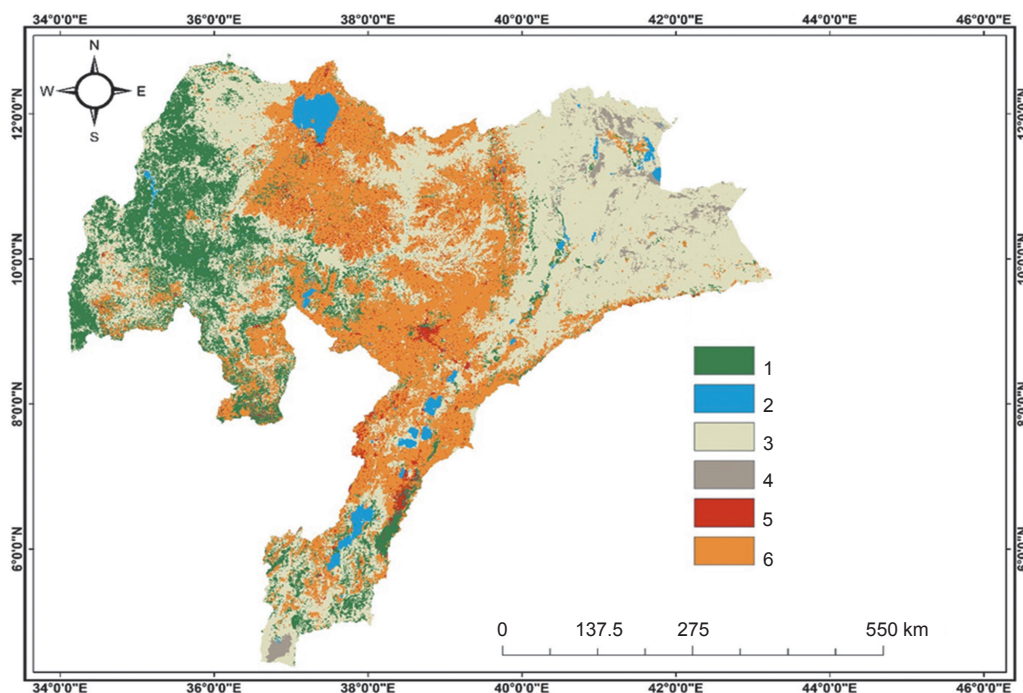


Fig. 5. Natural and man-made landscapes of the central part of Ethiopia (in accordance with GOST 17.8.02-88¹):

1–4 – natural landscapes: 1 – forest, 2 – water (lakes, rivers, flooded areas), 3 – steppe, 4 – deserts, semi-deserts, volcanic structures; 5, 6 – man-made landscapes: 5 – industrial and settlement landscapes, 6 – agricultural landscapes

Рис. 5. Природно-техногенные ландшафты центральной части Эфиопии (в соответствии с ГОСТ 17.8.02-88¹):

1–4 – природные ландшафты: 1 – лесные, 2 – водные (озера, реки, плавни), 3 – степи, 4 – пустыни, полупустыни, вулканические сооружения; 5, 6 – искусственные ландшафты: 5 – промышленные и поселения, 6 – сельскохозяйственные

¹ GOST 17.8.02-88. The interstate standard. Nature conservation. Landscapes. Classification. *Meganorm.ru*. Available from: <https://meganorm.ru/Data/196/19614.pdf> [Accessed 12th December 2024]. (In Russ.).

ГОСТ 17.8.1.02-88. Охрана природы. Ландшафты. Классификация // *Meganorm.ru*. Режим доступа: <https://meganorm.ru/Data/196/19614.pdf> (дата обращения: 12.12.2024).

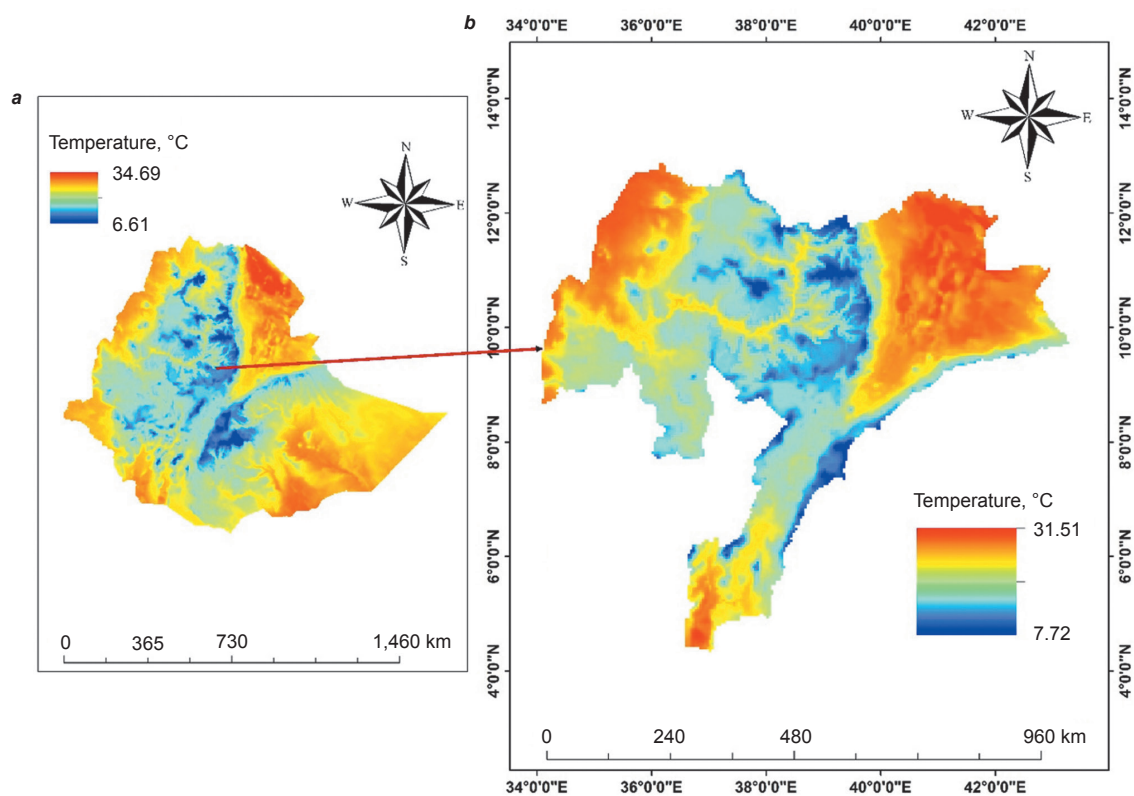


Fig. 6. Temperature distribution on the territory of Ethiopia in general (a) and in its central part (b)
Рис. 6. Распределение температуры на территории Эфиопии (a) и ее центральной части (b)

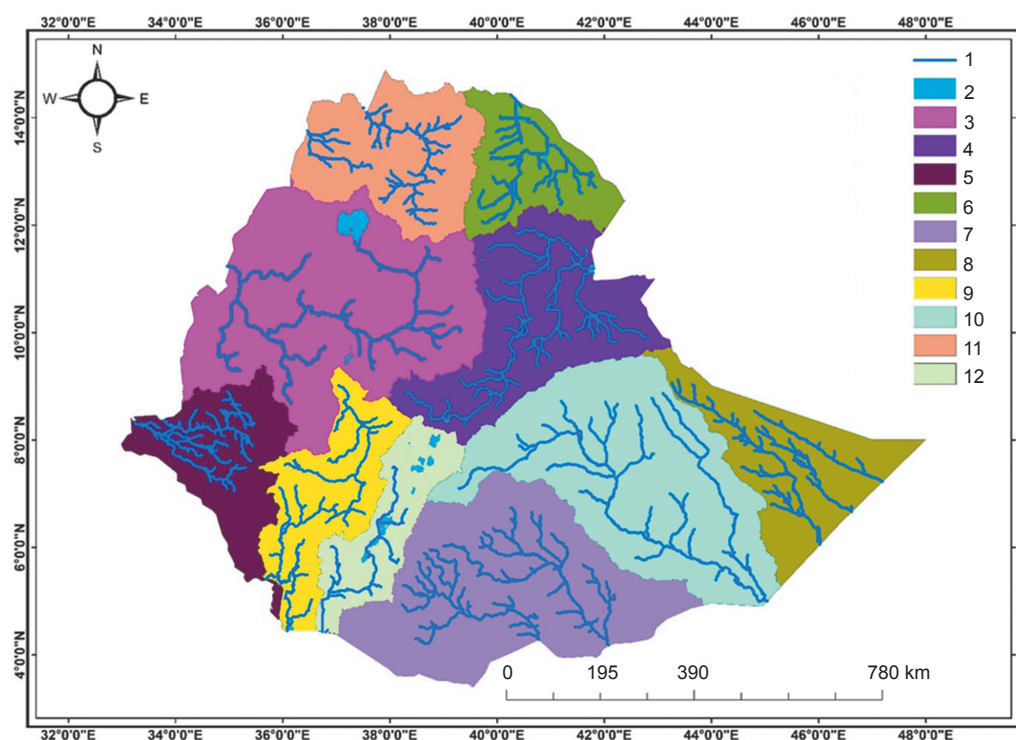


Fig. 7. River basins identified on the territory of Ethiopia:

- 1 – rivers; 2 – lakes; 3 – the Abbay Basin; 4 – the Awash Basin; 5 – the Baro-Akobo Basin;
6 – the Denakil DepBasin; 7 – the Genale Basin; 8 – the Ogaden Basin; 9 – the Omo Gibe Basin;
10 – the Wabshe Basin; 11 – the Tekeze Basin; 12 – Rift Valley Drainage Basin

Рис. 7. Речные бассейны, выделенные на территории Эфиопии:

- 1 – реки; 2 – озера; 3 – бассейн р. Аббай; 4 – бассейн р. Аваш; 5 – бассейн р. Баро Акоб;
6 – бассейн р. Денакиль; 7 – бассейн р. Генале; 8 – бассейн р. Огаден; 9 – бассейн р. Омо Гибе;
10 – бассейн р. Вабше; 11 – бассейн р. Текезе; 12 – водосборный бассейн рифтовой долины

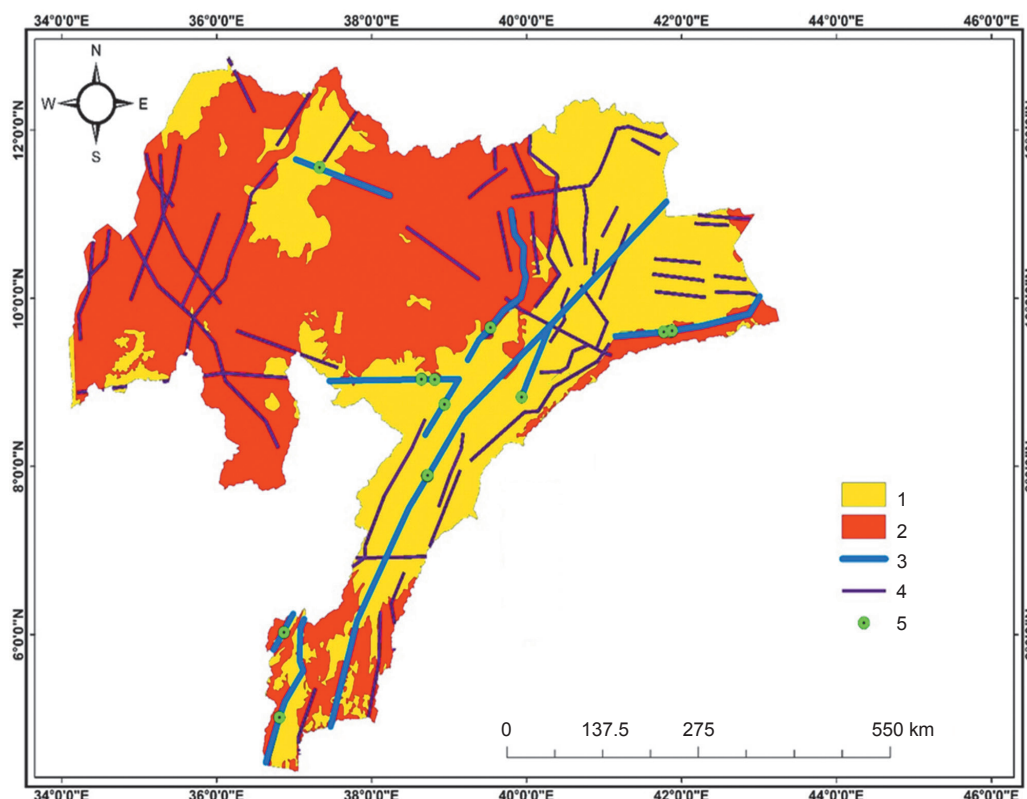


Fig. 8. Structural and hydrogeological diagram of Central Ethiopia:

1 – hydrogeological basins; 2 – hydrogeological massifs; 3 – (inferred) flooded faults;
4 – faults unexplored hydrogeologically; 5 – hydrogeological wells

Рис. 8. Структурно-гидрогеологическая схема Центральной Эфиопии:

1 – гидрогеологические бассейны; 2 – гидрогеологические массивы;
3 – предположительно обводненные разломы; 4 – разломы, гидрогеологическая роль которых не определена; 5 – гидрогеологические скважины

Wabishebele, Tekese, Awash, Danakil, Baro-Akobo, Omo-Gibe, and There is also a basin that unites surface waters confined to the southern part of the Rift Valley. Catchment areas range from 58,000 km² (Danakil River) to 207,000 km² (Abbay River).

As a result of tectonic development and geological and structural features of the territory of Ethiopia, the structural – hydrogeological conditions of the region have formed, which play a crucial role in the distribution of groundwater storage. Within Central Ethiopia, hydrogeological basins have been identified, confined to low relief areas and river valleys and composed mainly of loose quaternary sediments; hydrogeological massifs occupying mountainous areas and volcanic structures, represented by limestones, dolomites, intrusive and effusive formations²; flooded faults, formed mainly within the areas of carbonate sediment development (Fig. 8).

Conclusions

Thus, the structural and tectonic development of the territory, due to its confinement to the East African Rift Zone, played a decisive role in the formation of natural water resources in Ethiopia as a whole, and its Central part, in particular. The relief, climatic features, main geomorphological and geological structures are the result of past and neotectonic processes. Understanding the conditions of formation and distribution of surface and groundwater in the region, a significant volume of initial data, the use of modern means of its processing will allow us to quantitatively assess surface water resources and outline the most promising subsoil areas for exploration work on groundwater necessary to meet the economic and drinking needs of Central Ethiopia, especially during dry periods of the year. In the future, it is planned to develop the complex index of water abundance based on the results of assessing the geographical, geological-tectonic, structural-hydrogeological features of the study area.

² Alemu T. *General geology (geol 2081). Chapter 7: Geology of Ethiopia*. Addis Ababa; 2012, 11 p.



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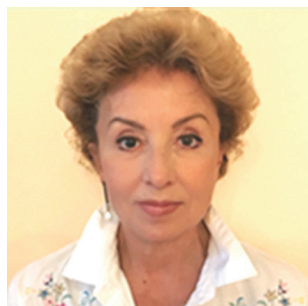
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