Integrated design and construction approach to hydrotechnical structures in Eritrea

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Abstract. During the process of design and construction of water management facilities and structures, such as reservoirs, dams, spillways, water intakes, etc., it is important to pay attention to the specific conditions of a particular country. Since the rapprochement among Eritrea, Ethiopia and Djibouti in 2018, the geopolitical dynamics of the region has changed to a different level. These regional changes will significantly contribute to the development of extractive and processing industries, agriculture, trade, construction and tourism in Eritrea. However, all these developments unquestionably require sustainable and efficient water use, intensive development of water management and water technologies, among others. Based on the specific conditions of Eritrea, identification of existing main trends in the design and construction of water management facilities and structures followed by formulation of practical recommendations and future directions has been the focus of this study. Reliable and relevant information has been processed and analysed using general scientific research methods, including generalization and analysis, synthesis and analogy, historical and hypothetical methods of cognition. This paper comprehended that the design, construction and operation of water management structures should consider the predominantly hot climatic condition of the country, while observing the main development trends in the field. These activities help in ensuring reliable and trouble-free operation of hydraulic structures, using modern and progressive achievements of hydraulic engineering science and global practice in the field of dam engineering and construction of culverts taking into account environmental requirements and norms, and using modern high-performance mechanisms and methods of production of hydraulic works. Moreover, the hydrological and water management conditions of Eritrea are characterized by limited water resources, poor knowledge of water bodies, and lack of reliable hydrological, meteorological and geological information. Under these circumstances, it would be necessary to use mathematical modelling for understanding and forecasting hydrological processes in river basins.

Introduction

During the process of design and construction of water management facilities and structures, such as reservoirs, dams, spillways, water intakes, etc., it is important to pay attention to the specific conditions of a particular country [1]. Various studies (e.g., [1]–[8]) were carried out and identified the following major specific areas that require a special consideration:

- climatic and socio-economic conditions,
- prospects and trends of economic development in conjunction with bordering countries,
• institutional and human capacity, experience and traditions of water resources development and management, and
• completeness and reliability of survey data, namely meteorological, hydrological, geological, geodetic, environmental engineering, etc.

Eritrea is a young independent state that had been consistently exposed to military operations for several decades, notably until 2000. The Gross Domestic Product (GDP) in Eritrea was worth USD 6.72 billion in 2018. The GDP value of Eritrea represents 0.01% of the world economy [9]. The country’s current state of affairs of underdevelopment is mainly due to war. Presently, about 80% of population depends on traditional subsistence agriculture. The share of agriculture in gross domestic product (GDP) is 11.7% in 2017. It possesses not only limited arable land (about 6.83%), but also experiences an acute shortage of fertile land due to prevalent and intensive soil erosion. A significant share of the agricultural sector is due to crop production (bananas, potatoes, corn, sesame, vegetables, papaya, millet, wheat, sorghum, cotton, citrus, etc.), whereas dairy, poultry and fishing farming are at their rudimentary stage of development [9]. Enterprises, such as footwear, food, textile, etc. of the manufacturing industry have been restored to a limited extent after independence. There are enterprises that process fish, meat and dairy products, produce glass, soft drinks, and develop handicraft industry. Industrial extraction of salt from sea water has been established. Official reports from the government of Eritrea reveal that the mining industry has been booming since the beginning of the last decade, such as gold, copper, zinc and potash. The industrial sector contributed 29.6% to the country's GDP in 2017 [9].

During 1990-2018, construction in Eritrea increased by USD 1.09 billion (77.9 times) at current prices; the share of construction in Eritrea in 1990 was USD 0.014 billion at current prices, whereas it was USD 1.10 billion in 2018. The average annual growth of the construction industry was USD 0.039 billion dollars (16.8%) over the specified period. The share of construction in the world increased by 0.022%, while in Africa it increased by 0.69%. The construction of Eritrea in 2018 was equal to USD 1.10 billion and ranked 117th in the world, matching the level of construction in New Caledonia, Bolivia, and Jamaica [10]. Construction per capita in Eritrea was USD 212 in 2018, ranking 133rd in the world. It is comparable to the level of construction per capita in Bosnia and Herzegovina (USD 225.9), South Africa (USD 224), Moldova (USD 221.7), El Salvador (USD 213.4), and Cambodia (USD 205.1). However, construction per capita in Eritrea (USD 409.3) was less than construction per capita in the world (USD 621.3) [10].

Eritrea is bordered by the Red Sea in the northeast, Djibouti in the east and Sudan in the northwest and Ethiopia in the south and southeast. Over the past decade, Sudan, Ethiopia and Egypt have shown the willingness to work together so as to realize equitable and reasonable use of shared water resources. For instance, negotiations between the tripartite countries are on-going on the construction of “Grand Ethiopian Renaissance Dam” in the Upper Nile. This dam is sought to be the largest hydroelectric power plant in this part of the African continent. Ethiopia has attempted to develop its hydropower potential (about 40 GW) since 1980s and 1990s. These works have been up scaled intensively by developing hydropower potentials of the largest rivers in the last 10-15 years: the Blue Nile and the Omo. Initially, there were not large hydroelectric power plants in Ethiopia; for instance, the “Malka Wakana”, with a capacity of 150 MW, was built in 1988 by the Soviet Union specialists. In 2004, hydroelectric power plant “Gilgel Gibe I”, with a capacity of 184 MW, was put into operation on the Omo river, and the second stage of the hydropower plant “Gilgel Gibe II”, with a capacity of 420 MW, was launched in 2010. In 2009, the Tekeze hydroelectric power plant, having a capacity of 300 MW, was commissioned on the Tekeze River - a tributary of the Nile River whose 86% of flow is generated in Ethiopia.

A comparison of the construction industry in Eritrea and its neighbours in 2018 showed that it was more than that of Djibouti (USD 0.1 billion) by 90.9%, but less than that of Ethiopia and Sudan by 93.3% (USD16.5 billion) and 43.7% (USD 2.0 billion), respectively [10]. With the rapprochement among Eritrea, Ethiopia and Djibouti in 2018, the geopolitical dynamics of the region has shown a significant improvement. To cope up with the ever-increasing demands of the population, these
situations will definitely give regional governments to boost drastically extractive industries, agriculture, trade, tourism and the like. In this regard, sustainable and efficient water use, intensive development of water management and water technologies, among others, is crucial [2].

In view of the above facts, this paper attempts to identify the existing main trends in the design and construction of water facilities and structures in Eritrea that have not yet been formulated, thereby providing viable integrated approaches to the development and management of water resources.

1. Methods
The achievement of the previously mentioned goal was possible with the skilful use of appropriate tactical methods of scientific research. To deduce practical recommendations and directions for future design and construction of water facilities and structures are processed and analysed by using general scientific research methods: generalization and analysis, synthesis and analogy, historical and hypothetical methods of cognition, which are presented in the ensuing section.

2. Results and discussions
The topographic and climatic conditions of Eritrea are highly variable. The topography varies dramatically from the highest point in the central highlands at Mount Soira, 3,018 m above mean sea level; descending to sea level on the East, to the coastal desert plain and the arid Sudan border and finally falling to 75 m below mean sea level at Lake Kulul in the Danakil depression. The country experiences relatively similar climatic conditions with its neighbouring states. The predominantly mountainous relief (northern spurs of the Ethiopian Highlands) with elevations up to 3,248 m (Mount Asimba), turning into flat or hilly part of the Afar depression in the east possess similar climatic characteristics. Most of the Eritrean territory is occupied by the extension of the Ethiopian Highlands.

Eritrea is located within the tropical climate zone with some of its features are being caused by the geographical location of the country: proximity to the Red Sea, length of the hilly mountainous highland dissected by channels and depressions that stretch from north to south and variety of terrains. Generally, its climate can be divided into three major zones: central highland, coastal region, and western lowlands. Each climate zone has a different pattern. According to Köppen climate classification, the country possesses either a hot semi-arid climate or a hot desert climate, although temperatures are much moderated at the highest elevations. There are two rainfall regimes, summer and winter, whose pattern is affected by physiographic regions. The summer rains, which are primarily concentrated in July and August, affect completely the central highland and the western lowlands. The south-westerly monsoon winds are responsible for the main rainy season. The winter rains which occur from November to March, which are brought about by the north and north-easterly continental air streams, affect the coastal and the eastern and southern escarpments, which are also part of the central highlands.

Along the Red Sea coast, a hot and dry desert climate dominates; for example, in the city of Massawa, the average July temperature is about 35 °C and the average January temperature is 26 °C. In summer, when the south-western monsoons blowing their moisture to the western slopes of the central highlands, there is no rain at all. Therefore, very hot and dry winds blow as a rule within Eritrea. The main share of precipitation on the coastal area falls in the winter months when there are thunderstorms; Massawa receives less than 200 mm rainfall. Rains are brought by north-eastern monsoon winds, which are dry in the Arabian Peninsula and become saturated with a small amount of moisture over the Red sea. The eastern slopes of the highlands delay the winds, thereby producing rainfall in the eastern escarpments and coastal areas. The amount of precipitation in the coastal desert decreases to the South and south east; for example, the port of Assab receives only a few centimetres of rainfall annually.

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The mountainous inland parts of Eritrea have relatively cooler and wetter climate. Precipitation in this region is occurs predominantly in summer season and have a torrential nature. Their frequency generally increases with the increase in the height of the mountains. The north and northeast receive
annual rainfalls ranging from 250 to 500, and southern highlands and south-western lowlands receive annual rainfalls ranging from 500 to 1,000 mm. For example, the meteorological station in Mendefera, located at an elevation of 2,022 m, receive 450 mm of annual rainfall for the three summer months, whilst its average air temperature in summer does not increase above 21.5 °C and winter does not fall below 17 °C. The intra-annual distribution of precipitation corresponds to the third tropical type [2], which is typical for the sub-equatorial zone between 20° and 10° latitude, where the maximum precipitation falls in summer season, but almost absent in the dry winter season. In these areas, there are also wet and dry years, i.e., significant inter-annual fluctuations in precipitation occur. The average annual internal endogenous precipitation on the territory of the country is estimated to be 384 mm or 45 billion cubic meters.

Reports from the Ministry of Land, Water and Environment, soil cover of Eritrea is as diverse as the topography and climate of the country. Soils in the highland areas, especially in the depression areas with some colluvial materials, the soils are relatively deep. But, soils of shallow depth are prevalent in the vast majority of the country. In general, the soils are of sandy texture, including sandy loam where parent materials are derived from granite, genies, sandstone and quartzite. Soils of lowlands are shallow, gravelly, and stony soils with coarse or very coarse texture. As such, the soils are classified as chromic luvisols, eutric cambisols, lithosols and haplic, xerosols. Soils of coastal plains are of coarse texture with sand, loamy sand and sandy loam. In the coastal plains, soils are also calcareous; they are either dark brown or dark grey brown in colour. In the north coastal areas, regosols are dominant, whereas in the southern part of Danakil plains, saline soils dominate, followed by regosols and lithosols. Soils of western plain belong to yermosols, regosols, chromic vertisols, cambisols, luvic, xerosols and fluvisols. Intensive soil erosion is visible and worrisome in the country, which is primarily linked to the nature of the rainfall and land degradation. Highland areas possess the most favourable climate and soil. However, areas located below 1,500 m below mean sea level are characterized by high air temperatures. Increased evapotranspiration lowers the soil moisture content that ultimately affects the agricultural productivity of the land.

Eritrea's water resources are limited. Flows through a large number of small and large channels occur during the rainy season, but remain dry for much of the year with the exception of Setit (Tekeze). Setit, the only perennial river that forms the border with Ethiopia, could not be fully utilized so far for major national development projects. Setit and the seasonal Mereb-Gash river - which crosses the western plain of Eritrea from east to west - belong to the Nile River basin. Unlike the Setit River, the Mereb-Gash waters do not join the Nile directly; rather they are lost in the sands of the east Sudanese plains. Barka-Anseba river basin is a combined basin of two rivers, namely Barka and Anseba; both originate from the central highlands of Eritrea, flowing north-west. They meet near the border with Sudan and eventually empty their contents into the Red Sea. The Red Sea river basin consists of the entire area along the Red Sea coast. It does not have a definite single main river instead, a number of small rivers directly draining in to the Red Sea. The Danakil Depression river basin lies along the south-eastern border of Eritrea and drains into the Danakil depression. Due to its closed topography and arid climate, Danakil river basin, unlike the other river basins, is characterized by highly saline soils with little agricultural potential. Three of the major river basins, namely Setit, Mereb-Gash and Barka-Anseba, have a considerable potential for generating hydroelectric power. However, it is worth to note that the flows through the various channels carry a huge amount of sediments because of soil erosion. The average long-term annual river flow on the windward slopes of the highlands increases to 300 to 500 mm when the runoff coefficient is greater than 0.2 to 0.3 [2]. Internal renewable water resources (IRWR) provided by the long-term average annual water content of rivers and replenished by internal precipitation are about 3 billion cubic meters [11].

The total annual volume of domestic renewable water resources per capita is decreasing every year due to population growth. In 2017, IRWR per capita was 552 cubic meters per year. IRWR per capita per year declined moderately from 775 cubic meters in 2002 to 552 cubic meters in 2017, declining by almost 30% [11]. A total natural renewable water resource (TRWR) corresponds to the maximum theoretical yearly amount of water actually available for a country at a given time. It makes up the...
long-term average sum of IRWR and external natural renewable water resources (ERWR). In 2017, TRWR was 1,443 cubic meters per capita per year, which is equivalent to 7.3 billion cubic meters per year for a population of around 5 million. There was almost 30% decline as compared to 2002 when the corresponding TRWR was 2,024 cubic meters per capita per year [11].

Dependency ratio is an indicator expressing the amount of total renewable water resources, originating outside the country. A country with a dependency ratio of 0% does not receive any water from neighbouring countries, whereas a country with a dependency ratio of 100% receives all its renewable water from upstream countries, without producing any of its own. Eritrea's dependency ratio was 61.7% in 2017, showing that percentage of the total renewable water resources come from abroad [11]. The total capacity of all reservoirs in Eritrea was 0.04 cubic kilometres or 8.70 cubic meters per capita in 2015. The area occupied by large rivers, lakes and reservoirs (internal waters) in 2017 was about 1,660 thousand hectares or 14% of the total area of the country (117,600 square kilometres). Rivers and artificial reservoirs are primarily used for agriculture. The water availability in the territory of Eritrea is generally low as it is characterized, among other things, by a shortage of dynamic water resources. The meagreness of dynamic water resource could be explained by the large amount of evaporation, transpiration and infiltration losses that significantly affect irrigated areas.

In view of the aforementioned facts, the main features or specific conditions of Eritrea are formulated as follows:

- climatic conditions are complex: high temperature, evaporation and transpiration losses, tropical type (maximum in summer season and dry in the winter season) intra-annual rainfall distribution, significant inter-annual fluctuations in precipitation and recurrence of droughts,
- unfavourable soil conditions in agricultural terms which are characterized by insufficient moisture, poor fertility and severe land degradation,
- water resources are limited: rivers are not water-rich, flows through rivers occur at the time of rainy season, otherwise remain dry during the rest of the time, rivers carry a lot of sediment during high water flow, low water availability within territories and weak regulatory capacities on rivers,
- unstable socio-economic conditions: the war for independence as well as the border conflict with Ethiopia had led to huge economic and social upheavals, population growth, insufficient production capacity and increased growth rates of the construction industry, lack of high technology and limited investment,
- complex post-independence political and economic relations with individual bordering countries,
- high level of development of the construction industry in neighbouring countries (e.g., Ethiopia), including water and hydropower construction, and
- insufficient knowledge and skill in river basin water management,
- insufficient and unreliable hydrological, meteorological, geological, geodetic, and environmental data.

The undeniable fact is that the design, construction and operation of water management structures in this country would be implemented under hot climatic conditions. Therefore, the water management structures should be done in compliance with the main national and global trends. Such trends should ensure reliable and accident-free operation of hydraulic structures, use modern and progressive achievements of hydraulic science and global practices, apply new cost-effective engineering solutions based on the consideration of alternative options, ensure comprehensive environmental requirements and implementation of environmental protection measures, and use modern high-performance mechanisms and methods of production of hydraulic works.

3. Conclusions
The main recommendations for the design and construction of water management facilities in Eritrea are formulated as follows.
1. The design of water management structures within Eritrea’s territory should be carried out taking into account the limited water resources of rivers and lakes, unavailability of comprehensive studies of water bodies, and lack of reliable initial data: hydrological, meteorological, geological, geodetic, and environmental information. In these conditions, methods and tools that are based on mathematical modelling and forecasting of hydrological processes in river basins are most likely to be appropriate tools.

2. The water stored in artificial reservoirs should be used comprehensively, that is, in the interests of all possible water users: municipal, domestic, agricultural, industrial, hydropower, recreational, sanitary, and environmental releases. The possibility of using a reservoir for irrigation and water supply should be evaluated taking into account the natural and climatic conditions and the development requirements of the areas adjacent to the reservoir.

3. The choice of the most effective option for placing a hydroelectric site or a hydrotechnical structure should be made based on the results of engineering surveys as well as comparison of technical and economic indicators of the project. In addition, the environmental impact assessment and a set of measures that ensure the extraction of minerals that fall within the construction zone of the hydrotechnical structures require utmost attention.

4. When designing reserve or auxiliary spillway structures for passing safely major flood flows thereby preventing overtopping of a dam, it is necessary to use special design and technological solutions, such as earthen embankments that are eroded during high floods called fusible plug or collapsible dam. Besides, when designing water supply structures, parapet wall on the crest of a dam as well as the maximum flow rate that may exceed the water level of the reservoir should be given due consideration. In situations with alternating seasons of low and high amounts of rainfall and drying up of watercourses during dry seasons, it is possible to create small hydroelectric units from a small reservoir without spillway gates.

5. When designing water retaining structures such as dams in areas where mountains and foothills exist, it is advisable to use local construction materials. For instance, earth and rock fill dams with artificial impermeable materials, or dams made up of low-cement concrete (rolled concrete, especially lean rolled concrete (CSG type from unsorted ground-cement mix)) or stone concrete (RFCD type), which can significantly reduce the cost of the dam design and speed up its construction are highly recommended. To create small reservoirs that collect water during the rainy season and reserve it for the dry season, it is better to think of constructing low dams and use gabion structures, fabric shells, or even sand for their construction.

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