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Romanian Geographical Society – Prahova Branch,
39 Bucharest Avenue, Ploieşti 100680, Prahova County, Romania
Email: sgrprahova@gmail.com

Journal Office, RGS – Prahova Branch
Tel: +40 728 858 022
Email: cejgsd@gmail.com

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CONTENT

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Assessment of drought trends in the Senegal River Basin by a terrestrial water storage index (GRACE)

Cheikh Faye*
Department of Geography, UFR Sciences and Technologies, Assane SECK University of Ziguinchor, Laboratory of Geomatics and Environment, BP 523 Ziguinchor, Senegal;
cheikh.faye@univ-zig.sn

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Abstract: Droughts lead to significant environmental and economic consequences, especially in arid and semi-arid areas like the Sahel. While site-level assessments of drought in the Sahel are abundant, assessments at the scale of entire hydrological basins are less common. Here, we use a new drought index called the terrestrial water storage index (TWSI) to assess trends in drought throughout the Senegal River Basin. This area covers parts of Guinea, Mali, Senegal, and Mauritania, the study period is between 2003 and 2020. Over the entire period, water storage in the Senegal River Basin is increasing by 0.87 km^3 y^{-1} on the total area of the basin. However, we observed two distinct phases within the time period: an overall water deficit between 2003 and 2012 and a surplus between 2013 and 2020. We also found variations in terrestrial water storage from highly negative at the end of the dry season (-12.47 cm in May 2003) to strongly positive at the end of the rainy season (15.30 cm in September 2020). Our study suggests that the TWSI can be a useful index for regional hydrological drought monitoring, especially for areas where meteo-hydrological observations are insufficient.

Key words: terrestrial water storage, GRACE, drought index, groundwater resources, Senegal River Basin

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1. INTRODUCTION

Groundwater in the Senegal River Basin, an important agricultural production area in Senegal, is of great importance for water resources management, agricultural development and ecosystem health in the region. These water resources are suffering the impacts of climate change and drought, which have become a serious natural disaster in Senegal in recent decades, resulting from low and erratic rainfall and high rates of evapotranspiration [1–7]. Several prolonged and severe droughts have caused severe water shortages, desertification and dust storms in many areas [8]. Monitoring changes and trends in drought in Senegal would generate important information that can be used to improve water resources management and disaster prevention [9].

Due to the increased ability of remote sensing systems to capture large-scale changes in spatio-temporal soil surface conditions, remotely sensed data and products have been incorporated into the monitoring methodology for meteorological, hydrological and agricultural drought, since the 1980s [10]. Among these remote sensing products, the Terrestrial Water Storage (TWS) data extracted from the gravity recovery and climate experiment (GRACE) have been successfully applied to drought monitoring. Numerous drought indices have been developed to quantify complex drought processes and to demonstrate actual hydrological conditions using a single measure from different perspectives on moisture conditions, deficiencies or excess water in a given area [11]. The two most commonly used

* Corresponding author: cheikh.faye@univ-zig.sn; Tel.: +221 775 071 519

drought indices are the Palmer Drought Index (PDSI) and the Standardized Precipitation Index (SPI) [12,13]. The most recent standardized precipitation-evapotranspiration index (SPEI), which would have been superior to the two previous indices, has been applied in some comparative studies [14]. It is generally accepted that SPIs and SPEIs are more sensitive to drought factors such as precipitation and evapotranspiration and offer improved drought prediction capabilities, particularly with regard to short-term droughts [15].

GRACE data have been used by several authors to characterize and monitor droughts and floods by observing changes in water storage [10,16,17]. Some drought indices have been developed from the changes observed by satellite in terrestrial water storage from GRACE data. From a time series of GRACE, we can quantify the time of occurrence of hydrological drought and its duration and severity [18]. Results suggest that GRACE-generated groundwater storage is strongly correlated with rainfall indices over most areas. Indeed, GRACE-based drought characteristics are consistent with SPI results in some areas [19]. The motivation for including these two indices of climate drought is that the temporal agreement between the hydrological data and these indices using precipitation and evapotranspiration in their formulations is strong, even under different climatic conditions [15].

The strong correlation between the drought indices (based on meteorological data) and GRACE's terrestrial water storage data (independent of meteorological data) can be used for validation and to demonstrate applicability from these datasets to the prediction of drought in some areas [10,20]. We therefore analyzed the interannual variation of terrestrial water storage while indicating the relationships between the variations of the SPI and the SPEI and the variability of the spatiotemporal data of GRACE from 2003 to 2020 in the Senegal River Basin. The objectives of this study were (1) to make a temporal evaluation of the relationship between the GRACE data set and drought indices and (2) to advise on the application of drought indices to detect patterns of drought affected by variations in terrestrial water storage under climatic conditions in Senegal.

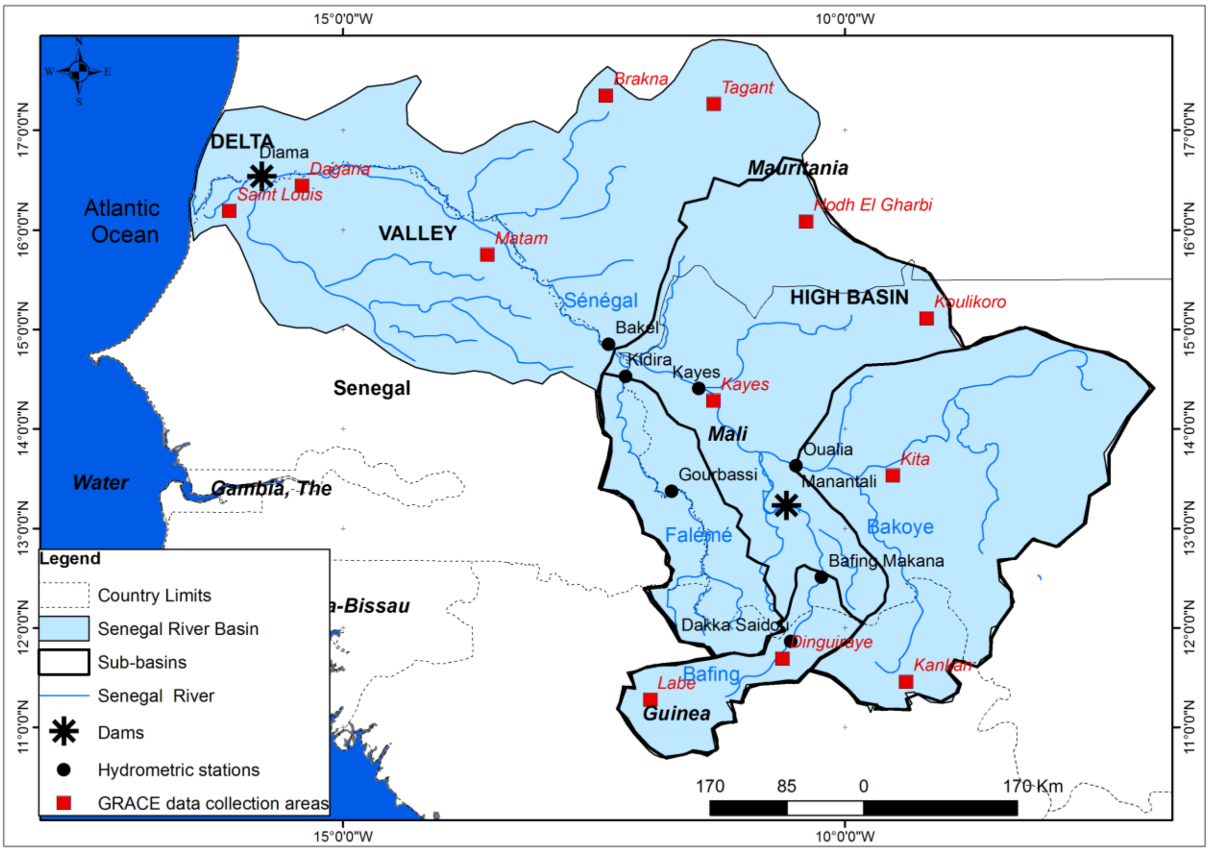


Figure 1. Situation of study stations in the Senegal River Basin.
Source: Senegal River Development Organization (OMVS), 2021

2. STUDY ZONE

The Senegal River covers four countries: Guinea, Mali, Mauritania, and Senegal (Figure 1). The river is 1,700 km long and drains a basin of 300,000 km^2. One of the main tributaries is the Bafing river. The Bakoye and Faleme tributaries, which also have their sources in Guinea, constitute with the Bafing tributary, the “upper basin” of the Senegal River [21] (Figure 1). The Senegal River is formed by the junction of the Bafing and Bakoye tributaries, then is joined by Kolimbiné, then by Karokoro to the west and the Falémé to the east, 50 km upstream of the city of Bakel in Senegal. In the southern part of the basin, the density of the hydrographic network is an indicator that soils are highly impermeable and water runoff into streams is high [22,23].

The Sahelian zone, in which the Senegal River is formed, was documented by inter-decadal patterns of drying and rewetting. While there is still debate on what drives these patterns, they are related to well documented ecological change. For example, various studies on the hydrology of the Senegal River Basin have shown changes in its hydrological regime, with the decline in flow rates during the period of the great drought from the 1970s [1–7,24,25]. In addition to changing climate patterns, human-built infrastructure has caused major changes to the hydrological dynamics of the Senegal River basin, specifically the large dams built at Diama and Manantali.

The Senegal River basin is generally divided into three entities: the “upper basin”, the valley and the delta, strongly differentiated by their topographical and climatological conditions. For this study, we focus on the entire basin, with selected stations on the Guinean, Malian, Senegalese and Mauritanian parts. On each part, the three stations are randomly selected from those that had data that is derived from the GRACE product. The Guinean and Malian parts of the river basin provide almost all of the water supply (over 80% of the inflow) up to the town of Bakel because of the higher precipitation rates in those areas [21]. In this area, rains fall between April and October in the mountainous part of the extreme south of the basin, especially in the Guinean part of the basin, and cause the annual flood of the river which takes place between July and October. For example, at the Labé station in Guinea (in the extreme south of the basin), the annual rainfall amounts vary between 1500 and 2000 mm for a total recorded annual mean rainfall of 1612 mm during the period 1933-2004 [2].

3. METHODS AND DATA

3.1. Data

3.1.1. GRACE terrestrial water storage data

To analyse the interannual variation of terrestrial water storage in the Senegal River basin, we used GRACE data from a set of water level data from the French Space Center (CNES / GRGS, current version: RL03-v3.monthly, available at: http://www.thegraceplotter.com). The National Aeronautics and Space Administration (NASA) and Deutsches Zentrum für Luft-und Raumfahrt (DLR) joint satellite mission, the Gravity Recovery and Climate Experiment (GRACE) mission launched in March 2002, is designed to measure small mass changes within the Earth over a large spatial scale [26]. The GRACE instrument represents one of newest observational system to improve the estimate of hydrologic, glacier, ice-sheet and oceanic mass changes with unprece-dented accuracy, ~a few cm in the form of water thickness change [27]. GRACE is currently measuring the Earth’s mass redistributions with a spatial resolution longer than 300–600 km (half-wavelength) or finer and at monthly temporal resolution. GRACE is capable of observing the total (both surface and subsurface) water thickness change over an entire watershed or basin [28], and although at relatively coarse spatial and temporal resolutions, GRACE represents a revolutionary tool to address contemporary research problems in terrestrial hydrology.

We extracted data at two scales. To characterize the temporal evolution of the TWS data, the data were first selected on the whole Senegal River Basin (for this, the average value of the basin was used in the study). To characterize the spatial variability of the TWS data, data are then selected at the level of the four riparian states (Guinean, Malian, Senegalese and Mauritanian parts of the basin) because of three sites per state: Guinea (Dinguiraye, Kankan and Labé), Mali (Kayes, Kita and Koulikoro), Senegal (Saint Louis, Dagana and Matam) and Mauritania (Brakna, Hodh El Gharbi and Tagant) (Table 1).

Table 1. Characteristics of the stations for which GRACE data were extracted.

Country	Sites	Latitude	Longitude	Maximum water height (cm)	Minimum water height (cm)	Annual amplitude (cm)	Series trend (cm y^{-1})
Guinea	Dinguiraye	11.69	-10.62	30.89	-26.75	17.09	0.29
	Kankan	11.46	-9.39	32.52	-27.66	15.85	0.54
	Labé	11.28	-11.94	33.23	-25.55	22.74	0.23
Mali	Kayes	14.28	-11.31	20.84	-22.70	7.25	0.32
	Kita	13.53	-9.52	26.52	-20.52	9.70	0.51
	Koulikoro	15.11	-9.19	47.43	-12.07	6.41	-0.08
Senegal	Saint Louis	16.19	-16.13	15.62	-16.61	4.32	0.28
	Dagana	16.44	-15.40	14.33	-16.54	3.34	0.26
	Matam	15.75	-13.56	19.57	-16.46	5.61	0.68
Mauritania	Brakna	17.35	-12.38	12,17	-8.52	1.26	0.14
	Hodh El Gharbi	16.08	-10.38	12.94	-13.55	3.02	-0.32
	Tagant	17.27	-11.30	13.34	-7.41	0.77	0.07
Total basin				15.30	-12.47	6.87	0.30

Source: CNES / GRGS, 2020

Annual amplitude: 22.741 cm

The values of terrestrial water storage are estimated from GRACE RL03-v3.monthly terrestrial products in the form of anomalies (difference in the value of each month compared to the mean). Monthly terrestrial water storage values were calculated as deviations from the average value of period from January 2003 to December 2020. Missing data were interpolated as the average values of the points before and after the missing data period. The anomalies were expressed in centimetres of equivalent water thickness per year, where 1 cm of variation in water thickness represents a mass change equivalent to a water layer of 1 cm. Positive values meant that there was more water than in the past, while negative values meant less water than in the past.

3.1.2. Climatological data

The 2003-2020 monthly and annual climatological data for the Senegal River Basin used in this study are precipitation and potential evapotranspiration (PET) calculated from climatological data from the Kedougou station. Due to the lack of climatological data on the sites selected to characterize the TWSI, only the Kédougou station, which is also fairly representative of the basin, was used and the data are provided by the National Agency of the Civil Aviation and Meteorology (ANACIM). On the series used, the precipitation is measured, whereas the PET is calculated by the Penman-Monteith method. Monthly precipitation and potential evapotranspiration data are used to calculate the SPI and SPEI indices. The FAO–Penman–Monteith method (FAO-PM) was recommended as the standard PET method based on physiological and aerodynamic criteria [29] by Food and Agriculture Organization (FAO) and World Meteorological Organization (WMO). The FAO–PM method as given by FAO Irrigation and Drainage Paper No. 56 [29] as:

$$PET_{PM} = \frac{0.408\times\Delta\times(R_n - G) + \gamma\times\frac{900}{T_{mean}+273}\times u_2\times(e_s - e_a)}{\Delta+\gamma\times(1+0.34\times u_2)} ,$$

where PET_PM is the potential evapotranspiration (mm/d); Δ is the slope of the saturation vapour pressure function (kPa/°C); R_n is the net radiation (MJ/m^2/day) (MJ means megajoule), which was estimated from total incoming solar radiation measurements following the procedure of Allen et al. [29]; G is the soil heat flux density (MJ/m^2/day), which was considered as null for daily estimates; γ is the psychometric constant (kPa/°C); T_{mean} is the daily average temperature (°C), which is the average value of the sum of maximum and minimum temperature; u_2 is the wind speed at 2 m height (m/s); e_s is the vapor pressure of the air at saturation (kPa); and e_a is the actual vapor pressure (kPa).

3.1.3. Hydrological data

The hydrological data consist of monthly hydrometric surveys from the hydrometric stations of Kidira (in the Falémé sub-basin) and Bakel (at the outlet of the upper Senegal River basin). The data were made available to us by the Senegal River Development Organization (OMVS). The data are available from 2002 to 2020. The two stations obey criteria of continuity (absence of gaps), duration of the available information and quality of the data (stations well gauged and respecting the relationship between the water levels and past flows). Their choice is also explained by the fact that one (Kidira station) is in a sub-basin with natural flow (Falémé basin) and the other (Bakel station) with artificial and complex flow (cumulative contributions natural flow tributaries and developed tributaries).

3.2. Methods

3.2.1. Terrestrial water storage with GRACE (TWSA)

The GRACE Space Mission is a joint project of NASA (the US Aeronautics and Space Administration) and DLR (German Aerospace Center) to provide monthly solutions to spherical harmonic coefficients describing the Earth's gravity field and to monitor spatio-temporal variations. In the gravity field with unprecedented bi-satellite resolution and precision on spatial scales ranging from 400 to 40,000 km and time scales ranging from a few months to several years from March 2002 [26]. The main objective of the GRACE project is to quantify the terrestrial hydrological cycle by vertically integrated measures of water mass evolution from aquifers, soils, surficial reservoirs and snowpack, with an accuracy of a few millimetres in terms of high and low spatial (>500 km) and temporal (>10 days) resolutions [30]. There is currently no global observing network with the temporal and spatial resolutions needed to properly characterize the water balance at regional and continental scales; GRACE satellite data are therefore used to monitor groundwater storage anomalies, including soil moisture content, groundwater, snow and ice, biomass and unsaturated soils, and surface water in rivers, wetlands, natural lakes and artificial reservoirs. These measurements represent the total amount of water stored at the soil surface and in the subsoil in response to the frequency and severity of large-scale, extreme climate changes [10,31,32]. In addition, the GRACE-based water storage deficit (TWS) is defined as the difference between the time series values of the terrestrial water storage with GRACE (TWSA) and the monthly average of the TWS values [17], and given as follows:

$$TWS_{i,j} = TWSA_{i,j} - \overline{TWSA} \quad ,$$

where TWSAi,j is the GRACE-inferred TWSA time series for the jth month in year i, and $\overline{TWSA}$ is the long-term mean (from January 2003 to December 2020) of TWSA for the same month (the jth month in a year). Negative WSD represents deficits in land water storage compared to its monthly mean values, while a positive value signifies a surplus water storage. TWS lasting for three or more consecutive months are designated as drought events, according to Thomas et al. [17]. To better characterise droughts based on TWS, and to compare TWS with other drought indices, we normalised this parameter using the zero mean normalisation method into the TWSI as follows:

$$TWSI = \frac{TWS - \mu}{\sigma} \quad ,$$

where μ and σ are the mean and standard deviation of the TWS timeseries, respectively. The TWSI time series represents the average seasonal deviation from the average conditions, and its magnitude indicates the drought intensity.

3.2.2. Standardised drought indices

Drought phenomena are generally expressed and characterised using standardised indices. In this study, we used three types of drought indices, namely the SPI (Standardised Precipitation Index), SPEI (Standardised Precipitation and Evaporation Index) and SFI (Standardised Flow Rates Index), to characterize droughts, in the Senegal River Basin and compare them to the Terrestrial Water Storage indices (TWSI) obtained using GRACE data.

The SPI [33] is primarily a meteorological drought index based on long-term precipitation records adjusted to a probability distribution. This calculates SPI, the precipitation record is first adjusted to a gamma distribution, and then converted to a normal distribution using an equiprobability function.

Positive SPI values indicate that the wet conditions are more pronounced than the median precipitation levels, while negative values indicate that the dry conditions are more pronounced than the median precipitation levels [10]. The drawbacks of SPI come from the fact that only rainfall is taken into account, while the other meteorological factors are neglected. The main advantages of the SPI relate to its simple calculation and its multi-scale characteristics (for example, 1, 3, 6, 12 or 24 months) [34]. For example, time scales of 3 to 6 months are appropriate for drought analysis in agriculture, 1 to 2 month scales for weather drought analysis and 12 to 24 month scales for analysis hydrological drought. Numerous studies have shown that SPI can be used to characterise drought trends in the Senegal River Basin and serve as a reference for drought mitigation, local management of water resources and agricultural decision-making, taking into account its flexibility, its simplicity and its wide application in real observations [35].

SPEI [14]) represents an extension of SPI, which considers precipitation in combination with potential evapotranspiration. SPEI uses monthly precipitation and temperature levels for calculations [36]. Precipitation and temperatures calculated for potential evapotranspiration (PET) are obtained from data from the Kedougou station. It should be noted that the PET values are estimated using the Penman-Monteith method [37], which is more accurate than the Thornthwaite method [38], that is, commonly used in most research studies on SPEI. PET allows SPEI to perform better in monitoring drought, flow and soil moisture in the Senegal River Basin [39]. SPEI is often used to assess and monitor water resource management, climate change adaptation, sustainable agricultural development, and variability and trends in drought [10,35].

The SFI [40] uses past flows from the Kidira and Bakel hydrological stations. The IFS has a calculation procedure similar to that described for the SPI, that is, a distribution is fitted to the data and then transformed into a normal distribution. The IFS was developed to quantify the water deficit for multiple time scales that will reflect the impact of drought on the availability of different types of water resources for a given period of time [41]. Studying this index also makes it possible to distinguish dry months and years (deficits) from wet (surplus) months and years. A drought occurs when the SFI is consecutively negative and its value reaches an intensity of -1 or less and ends when the SFI becomes positive.

The three drought indices can be calculated on different time scales (1 month, 3 months, 6 months, 9 months, 12 months, 24 months). In this work, the 1-month time scale was used to show the storage deficit of earth water monitored by GRACE satellites [10].

4. RESULTS

4.1. Analysis of GRACE data on the various selected sites in the Senegal River Basin

Figure 2 shows the spatio-temporal configuration of the water depth trends (in cm) estimated from the GRACE data on sites located in the riparian states of the Senegal River Basin from 2003 to 2020.

These heights of water are a great variability in the basin, at the level of the different riparian states. In addition, there is a latitudinal gradient of land water storage in the basin that increases from north to south, in accordance with the rain which also increases from north to south of the basin.

In the Guinean part of the Senegal River Basin, the three selected sites all show the greatest variability of water levels throughout the basin. Thus the annual amplitudes are very high and of the order of 22.74 cm at Labé (for a maximum height of 33.23 cm and minimum of -25.55 cm), 17.09 cm at Dinguiraye (for a maximum height 30.89 cm and a minimum of -26.75 cm) and 15.85 cm at Kankan (for a maximum height 32.52 cm and a minimum of -27.66 cm). Next come the sites located in the Malian part of the Senegal River basin with annual amplitudes that are two to three times less than those noted on the Guinean sites. These annual amplitudes are of the order of 9.70 cm at Kita (for a maximum height of 26.52 cm and a minimum of -20.52 cm), 7.25 cm at Kayes (for a maximum height of 20.84 cm and minimum of -22.70 cm) and 6.41 cm at Koulikoro (for a maximum height of 47.43 cm and a minimum of -12.07 cm).

The fall in annual amplitudes is largely noted in the Senegalese and Mauritanian parts of the Senegal River basin, which records the lowest water level values in the whole basin. In the Senegalese part of the Senegal River basin, the annual amplitudes are only around 5.61 cm in Matam (for a maximum height of 19.57 cm and a minimum of -16.46 cm), 4.32 cm in Saint Louis (for a maximum height of 15.62 cm and a minimum of -16.61 cm) and 3.34 cm in Dagana (for a maximum height of 14.33 cm and a minimum of -16.54 cm). In the Mauritanian part of the Senegal River basin, the annual amplitudes are the lowest in the basin with only 3.02 cm at Hodh El Gharbi (for a maximum height of 12.94 cm and a minimum of -13.55 cm), 1.26 cm at Brakna (for a maximum height of 12.17 cm and a minimum of -8.52 cm) and 0.77 cm at Tagant (for a maximum height of 13.34 cm and a minimum of -7.41 cm).

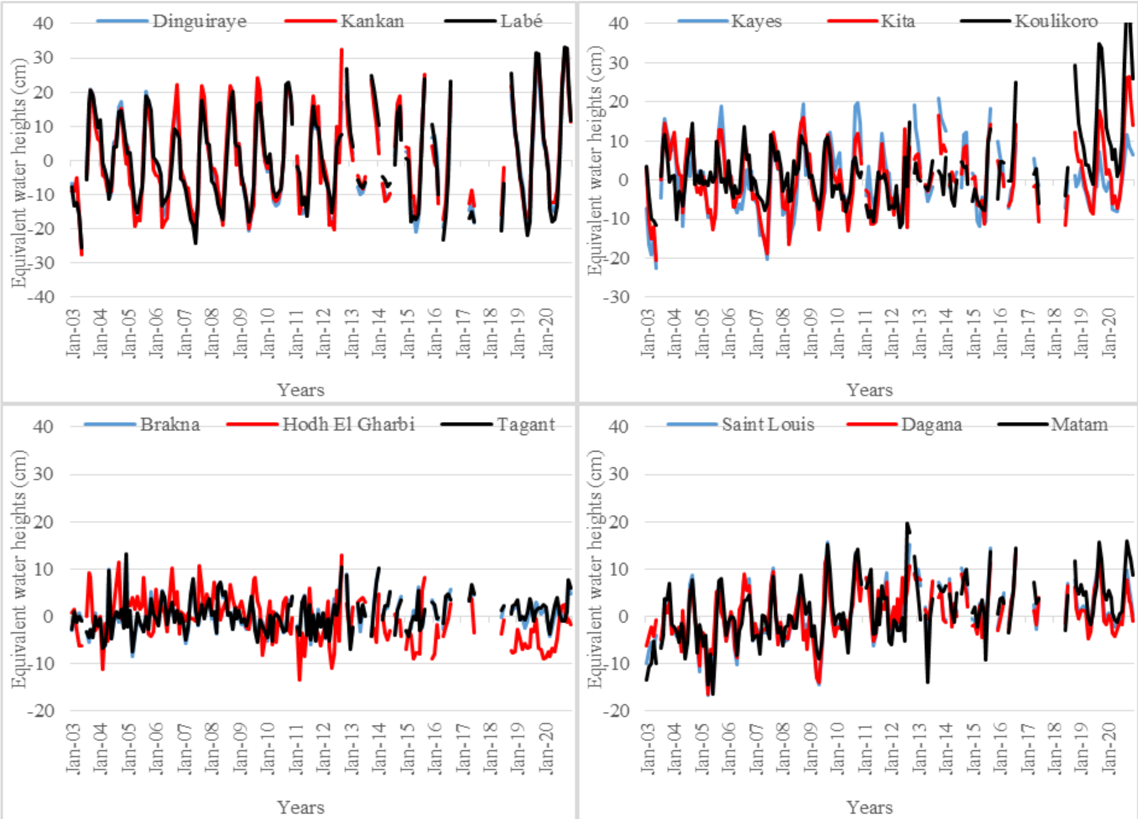


Figure 2. Monthly evolution of water depths (in cm) estimated from GRACE data on sites located in the riparian states of the Senegal River basin from 2003 to 2020.
Source: CNES / GRGS, 2020

In the Senegal River basin, a slight increase in stored water levels is noted in its various parts (upper, middle and lower basins and deltaic zone) and in the four riparian states (with the exception of Koulikoro in Mali with a trend of -0.08 cm/year and Hodh El Gharbi in Mauritania with a trend of -0.32). This upward trend is related to the improvement of rainfall and hydrological conditions in the basin since the 2000s in the West African zone [42–44], as indicated by the drought indices. The most obvious positive trends are found in different parts of the basin (0.68 cm/year in Matam, Senegal; 0.51 cm/year in Kita, Mali; 0.54 cm/year in Kankan, Guinea) as well as the weakest ones, although positive (0.28/year at Saint Louis and 0.26/year at Dagana in Senegal; 0.29 cm/year at Dinguiraye and 0.23 cm/year at Labé in Guinea; 0.32 cm/year at Kayes in Mali; 0.14 cm/year in Brakna and 0.07 cm/year in Tagant in Mauritania).

Figure 3, which also shows the annual evolution of the terrestrial water storage indices estimated from the GRACE data on sites located in the riparian states of the Senegal River Basin from 2003 to 2020, makes it possible to distinguish the different phases of the twelve selected sites and better highlight the obvious seasonal and interannual variations of terrestrial water storage in the basin.

On an annual scale, the analysis of land water storage indices from 2003 to 2020 allows two main phases to be distinguished on virtually all sites. The first phase runs from 2003 to 2012 with generally average annual water shortfall and therefore a negative index on the sites of the four states. Although the situation is more variable between 2003 and 2005 (down on some sites and up on others), on the other hand, from 2007 to 2009, the water level deficit is almost homogeneous at the different sites. In this phase, the deficit knows its largest magnitude over the period 2005-2012, despite the presence of years with positive indices such as 2003 (0.02 in Guinea), 2004 (0.2 in Guinea, 0.22 in Mali and 0.05 in Mauritania) and 2008 (0.1 in Mali and 0.47 in Mauritania). 2007 remains the year with most deficit (-0.28

in Guinea, -0.25 in Mali and -0.18 in Senegal). Over this year, the largest deficits are recorded at the Kayes (-0.53) and Kita (-0.34) stations in Mali and Labé (-0.39) in Guinea.

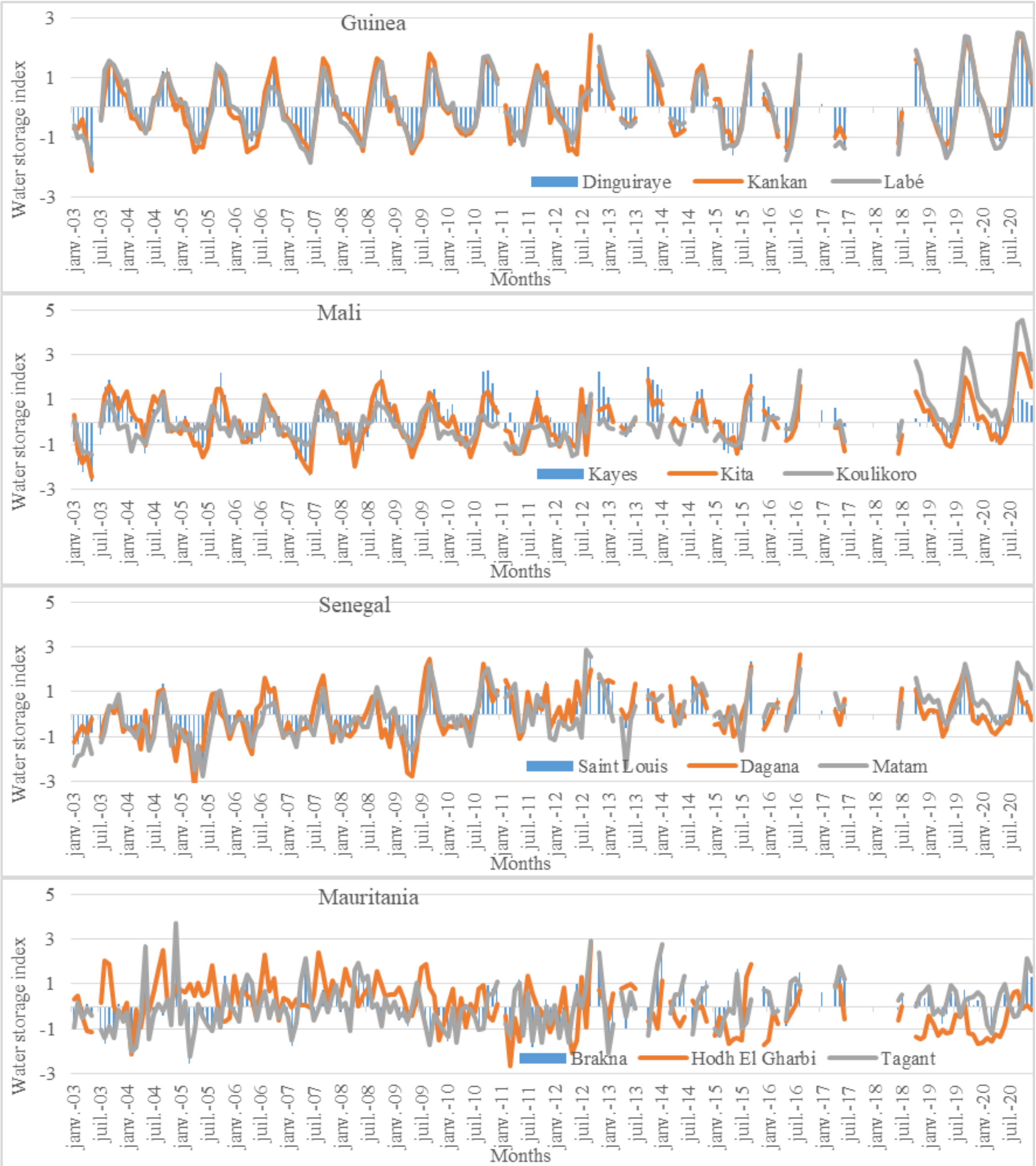


Figure 3. Annual evolution of terrestrial water storage indices estimated from GRACE data on sites located in the riparian states of the Senegal River basin from 2003 to 2020.
Source: CNES / GRGS, 2020

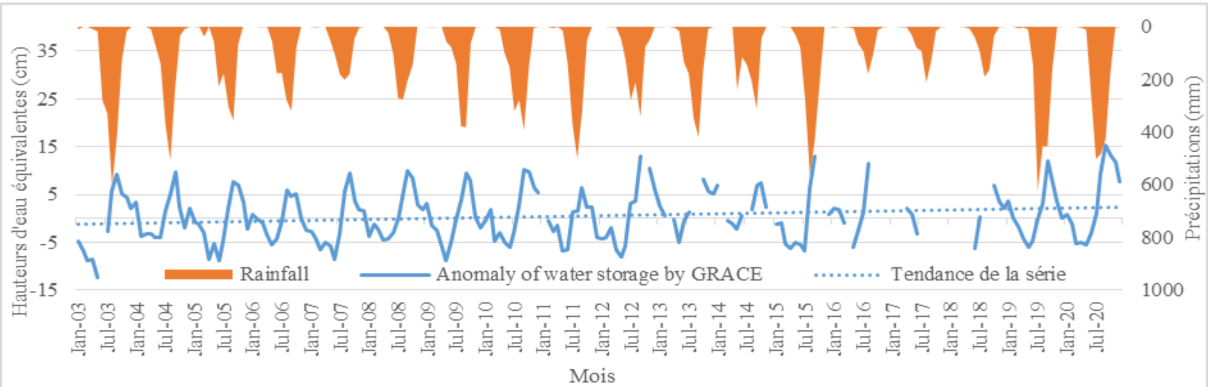
The second phase, which has a large surplus in land water storage, starts in 2012 and continues until 2020. Here, only a few years like 2015 (which recorded a negative index of -0.2 in Guinea, -0.16 in Mali and -0.36 in Mauritania), 2011 (-0.04 in Guinea, -0.35 in Mali and -0.44 in Mauritania) and 2012 (-0.15 in Mali) had deficits on average. Beyond this, all the years recorded an excess of water storage and that at the sites retained on the four residents of the basin. In this second phase, the year 2013 recorded the largest surpluses with 0.34 in Guinea, 0.38 in Mali and 0.5 in Senegal. Between 2012 and 2014, surpluses are the largest in the series. In 2012, indices can reach record highs in Senegal (0.75 in Dagana, 0.63 in Saint Louis and 0.54 in Matam). In Guinea and Mali, the highest positive indices are noted in 2013 with values that can exceed 0.3 (0.3 in Kankan and 0.45 in Labé in Guinea, 0.51 in Kita and 0.61 in Kayes in Mali). In the same year 2013, the indices are also very important in Senegal (0.65 in Saint Louis and 0.69 in Dagana) as well as in Senegal in 2014 (0.46 in Dagana, 0.58 in Saint Louis and 0.62 at Matam), Mauritania (0.54 at Tagant and 0.58 at Brakna) and Mali (0.38 at Kayes). This evolution reflects fairly well the rainfall anomalies during the period studied.

At the monthly scale, the analysis of the land water storage indices from 2003 to 2020 also makes it possible to distinguish two main seasons on practically all sites. The first season concerns the months of February to July marked by negative indices (although some positive) on the sites of the four states bordering the Senegal River basin. The month of April (-1 in Guinea, -0.82 in Mali and -0.55 in Senegal), May (-1.23 in Guinea, -1.08 in Mali and -0.7 in Senegal) and June (-1.04 in Guinea, -0.69 in Mali and -0.49 in Senegal) record the largest negative indices. The rest of the year (from August to January) concerns the second season during which the indices remain overall positive. The most important values are noted in August (0.42 in Guinea, 0.61 in Mali and 0.72 in Senegal), September (1.41 in Guinea, 1.27 in Mali, 0.38 in Mauritania and 0.34 in Senegal) and October (1.23 in Guinea, 0.86 in Mali and 0.58 in Senegal).

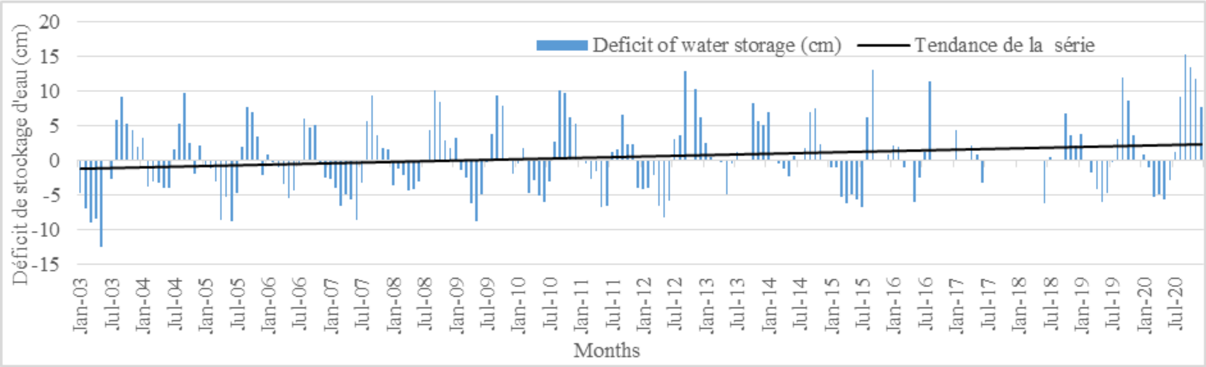
4.2. Analysis of the relationship between GRACE data and drought indices in the Senegal River Basin

To analyse the relationship between the GRACE data and the standardized drought indices in the Senegal River Basin, the average values of the GRACE data for the whole basin are used, from which the deficits and the storage indices are calculated of land water. The deficit of terrestrial water storage (TWS) is an important feature of the occurrence of drought. Figure 4a shows the temporal variations in average land water storage and associated precipitation from 2003 to 2020. In general, precipitation is well correlated with water storage anomalies from 2003 to 2020. The data were clearly revealed that the most significant precipitation occurred during the rainy seasons of 2012 and 2020, and that these periods corresponded to peaks in the TWS time series. At the annual scale, water storage increased at a rate of 3 mm/year between 2003 and 2020, while precipitation increased a little less strongly, at a rate of 0.25 mm/year. The same is true for flows that increased by 0.38 m^3/s/year in Kidira on the Falémé and 0.21 m^3/s/year in Bakel at the outlet of the “upper basin”. Thus the annual amplitude is of the order of 6.87 cm in the basin for a maximum height of 15.30 cm and a minimum height of -12.47 cm, significant deficits in water storage were recorded between 2003 and 2012 (Figure 3b). More specifically, deficits of -12.47 cm and -8.75 mm were detected in May 2003 and June 2005, respectively.

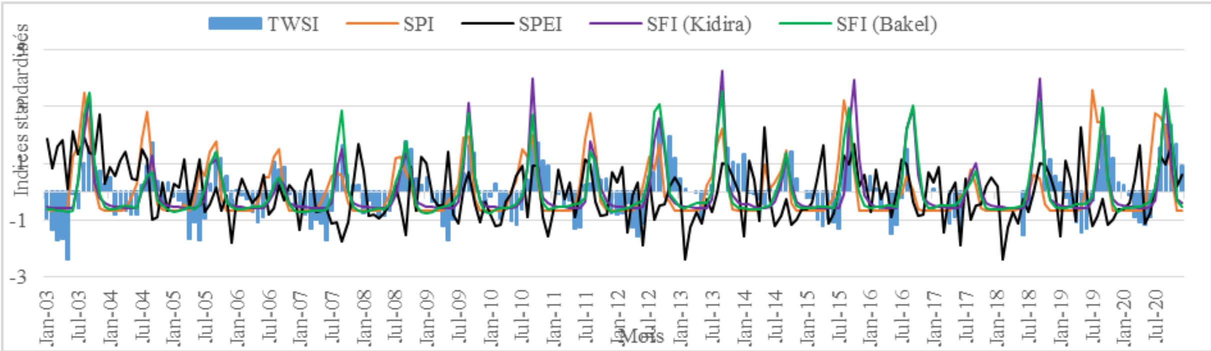
As of 2010, the annual water storage was mainly in surplus, with one obvious exception of water storage deficit detected in 2011 (with an average deficit of -0.72 cm and a total of 7 months all deficit) and 2020 (with an average deficit of -3.94 cm and a total of 5 months, ranging from February to June, all in deficit). On the other hand, the years 2010, 2012, 2013 and 2014, 2018 recorded excess water storage, with an average surplus of the order of 1.14 cm, 0.48 cm, 1.14 cm and 2.46 cm respectively. According to the definition of a drought episode [17], seven droughts were confirmed on the basis of land-water storage during the period 2003-2020 in the Senegal River Basin (Table 2). The number of deficit months in the driest years is between 6 and 8 months. The 2005 and 2006 periods were the two most important drought periods in the basin, with respective durations of 8 months. The peak deficits recorded in May 2003, June 2005 and May 2009 (referred to as the most severe drought events) were -124.7 mm, -87.2 mm and -86.9 mm, respectively. Beyond these years, others like 2007, 2012 and 2020 had a respective average deficit of -50.9 mm, 51.2 mm and 55.6 mm.



(a)



(b)



(c)

Figure 4. Time series from 2003 to 2020: (**a**) Evolution of precipitation and anomaly of GRACE-inferred terrestrial water storage (TWSA); (**b**) Evolution of the water storage deficit (TWS), and (**c**) Evolution of standardized indices (TWSI, SPI, SFI).
Source: CNES / GRGS and OMVS, 2020

Table 2. Summary of drought episodes identified by GRACE in the Senegal River basin from 2003 to 2020.

Years	Duration (number of months)	Average deficit (mm)	Peak deficit		Total gravity (mm)
			Values (mm)	Dates	
2003	6	-73.4	-124.7	May	-440
2004	6	-33.2	-40.0	June	-199
2005	8	-43.0	-87.2	June	-344
2006	8	-21.7	-54.2	May	-174
2007	7	-50.9	-86.7	June	-356
2008	6	-31.3	-44.0	A vril	-188
2009	7	-36.9	-86.9	May	-258
2010	6	-36.9	-59.4	June	-221
2011	6	-36.3	-67.0	May	-218
2012	6	-51.2	-81.5	May	-307
2013	3	-18.7	-49.4	May	-56.2
2014	3	-17.8	-23.0	May	-40.1
2015	7	-43.9	-66.9	June	-307
2016	-	-	-59.7	May	-
2017	-	-	-	-	-
2018	-	-	-62.5	June	-
2019	5	-33.4	-60.6	May	-130
2020	5	-39.4	-55.6	May	-178

Source: CNES / GRGS, 2020

Figure 4c shows the comparison between the Terrestrial Water Storage Index (TWSI) and the three most commonly used drought indices, namely SPI, SPEI and SFI in the Senegal River basin from 2003 to

2020. An analysis of the relationship between the GRACE dataset, the SPI, the SPEI and the SFI showed good agreement on certain years and seasons. However, because these indices are formulated using different variables and methodologies, some behavioural differences have also been observed. Thus, for certain months, seasons and years, the storage values do not really reflect the evolution observed on climate indices. For example, the TWSI index was lower than other indices in some years such as 2003, 2007, 2012 and 2015 and generally higher than the three indices of other years. As for the SPI, SPEI and SFI indices, they are marked by great variability and have a nearly identical evolution over the period of study in the basin. They record some negative values over the periods 2005-2012 and 2013-2020 (which reflects drought conditions), sometimes positive over the years 2003, 2004, 2010, 2011, 2015, 2019, 2020 (which reflects humidity conditions). The year 2013 remains exceptionally the only one of the series of which the SPI is positive (0.05) and the SPEI is negative (-0.54).

Table 3. Correlation matrix of drought indices in the Senegal River basin from 2003 to 2020.

	TWSI	**SPI**	**SPEI**	**SFI (Kidira)**	**SFI (Bakel)**
TWSI	1.00				
SPI	0,40	1.00			
SPEI	0,02	0,17	1.00		
SFI (Kidira)	0,69	0,66	0,12	1.00	
SFI (Bakel)	0,66	0,73	0,10	0,95	1.00

Source: CNES / GRGS and OMVS, 2020

Although the water storage deficit can be used to quantify the extent of a water deficit, it does not reveal the differences in the intensity of a water deficit. In general, the behaviour observed for the water storage index and its response to climate anomalies were reasonably consistent with the other indices examined in this study. Table 3 shows the estimates of correlations between the four drought indices. The correlation coefficients show a significant correlation between the TWSI and other drought indices, including SPI and SFI (at a 95% confidence interval), as well as a similar associated internnual trends. The most important TWSI correlation coefficients are with SFI at Kidira station at 0.69 and SFI at Bakel station at 0.66. SFI is therefore better correlated with TWSI than with other indices, suggesting that droughts are more dependent on runoff production and soil moisture characteristics. Between the SPI and the SFI, the correlation is also relatively important and of the order of 0.73 at Bakel and 0.66 at Kidira. The SPI and the SPEI showed the lowest correlation coefficients, but positive with 0.17. Evapotranspiration is the only difference between SPEI and SPI, and the stronger correlation between TWSI and SPI (0.40) than between TWSI and SPEI (0.02) suggests that precipitation is more responsible for soil release than the difference between rainfall and evapotranspiration in the Senegal River Basin between 2003 and 2020. Overall, strong correlations were determined between the three standardised drought indices, which were also reliably correlated with the TWSI.

4.3. Spatial distribution of GRACE data in the Senegal River Basin

4.3.1. Inter-annual distribution of GRACE data

To better understand the interannual spatial variations of GRACE-based terrestrial water storage in the Senegal River Basin, we have spatialised the average values of water storage over a three-year period (Figure 5).

As shown in Figure 5, changes in groundwater levels based on GRACE indicate rapid depletion of groundwater over the period 2003-2005 (7 out of 12 sites have negative values), 2006-2008 (8 sites out of 12 record negative values) and 2009-2011 (6 sites out of 12 record negative values). This decrease in values is consistent with the decrease in precipitation over the same year. On the other hand, the period 2012-2014, considering the increase of the rain, generally registered positive values, with the exception of Koulikore (-0,87 cm) and Hodh El Gharbi (-1,64). In addition to go further into the analysis, we can split the series into two parts, From 2003 to 2009, water storage anomalies are negative (only Koulikore with 1.08 cm and Hodh El Gharbi with -0.09 cm recorded positive values), which is quite consistent with the relatively low rainfall over this period. After that, the groundwater level showed a substantial increase from 2013 to 2020 with the increase in annual rainfall totals (only Koulikore with -1.46 cm and Hodh El Gharbi with -1.77 cm recorded negative values).

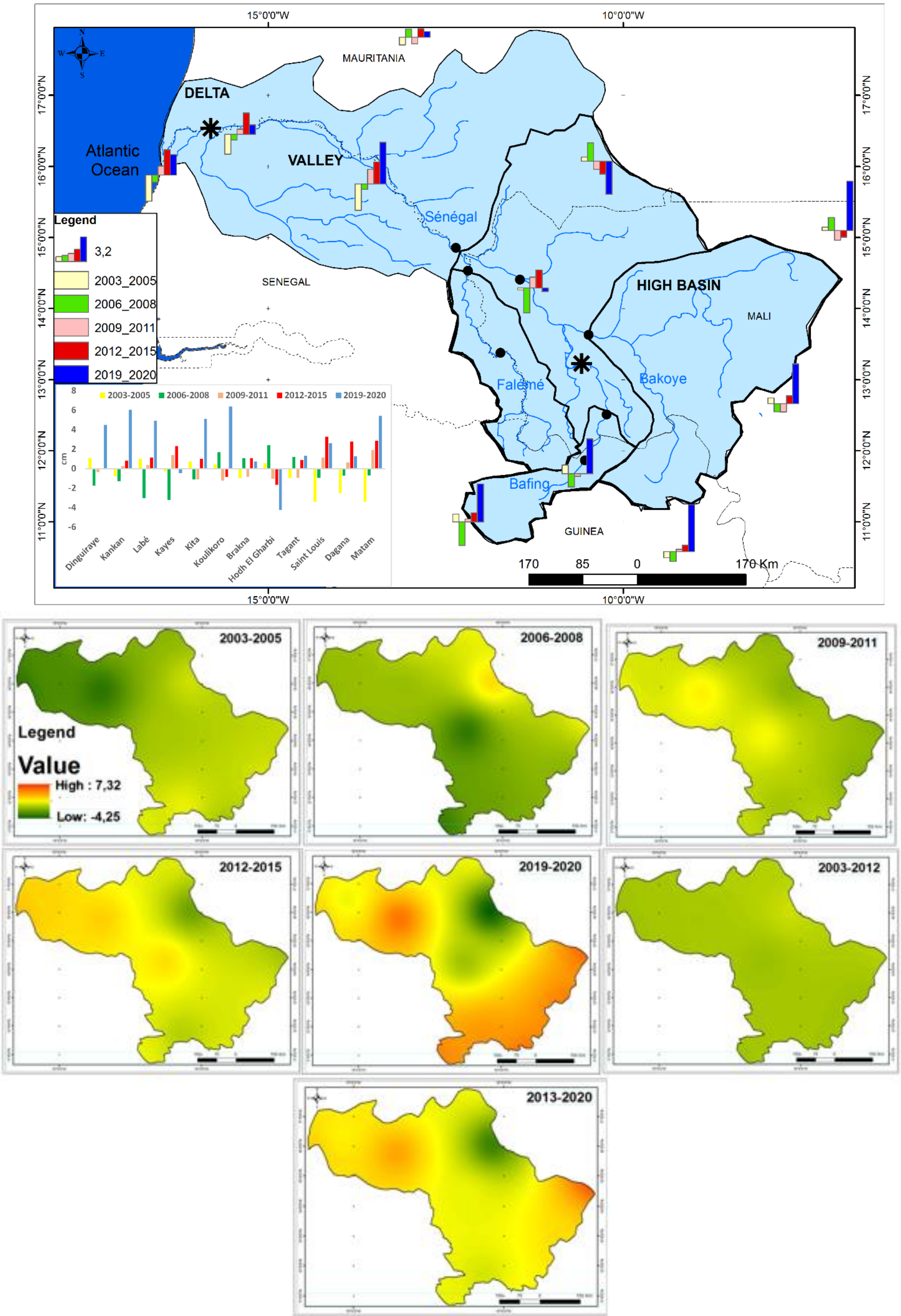


Figure 5. Interannual spatial variations in water depth (in cm) estimated from GRACE data for the entire Senegal River Basin by periods from 2003 to 2020.
Source: CNES / GRGS and OMVS, 2020

There is therefore a fairly good agreement between the inter-annual variations of water storage based on GRACE and those of rain in the basin. In general, when the annual precipitation anomaly is negative, the annual depletion of groundwater is also negative; and vice versa. However, in the basin, observed year-to-year variations in groundwater levels are not always consistent with rainfall data (such as the case of 2003 and 2004 where water level anomalies are negative for water storage) and positive for precipitation). This concordance of anomalies is more noticeable between 2005 and 2012 (with negative values on both parameters) and between 2010 and 2011 (with positive values on both parameters).

4.3.2. Seasonal and monthly distribution of GRACE data

Figure 6 shows the monthly distribution of spatial variations of GRACE-based terrestrial water storage in the Senegal River Basin.

At the different sites, the months that record negative storage anomalies are generally the months of February to July (coinciding with the dry season) and those whose anomalies are positive are the months of August to January (coinciding with the seasonal rains).

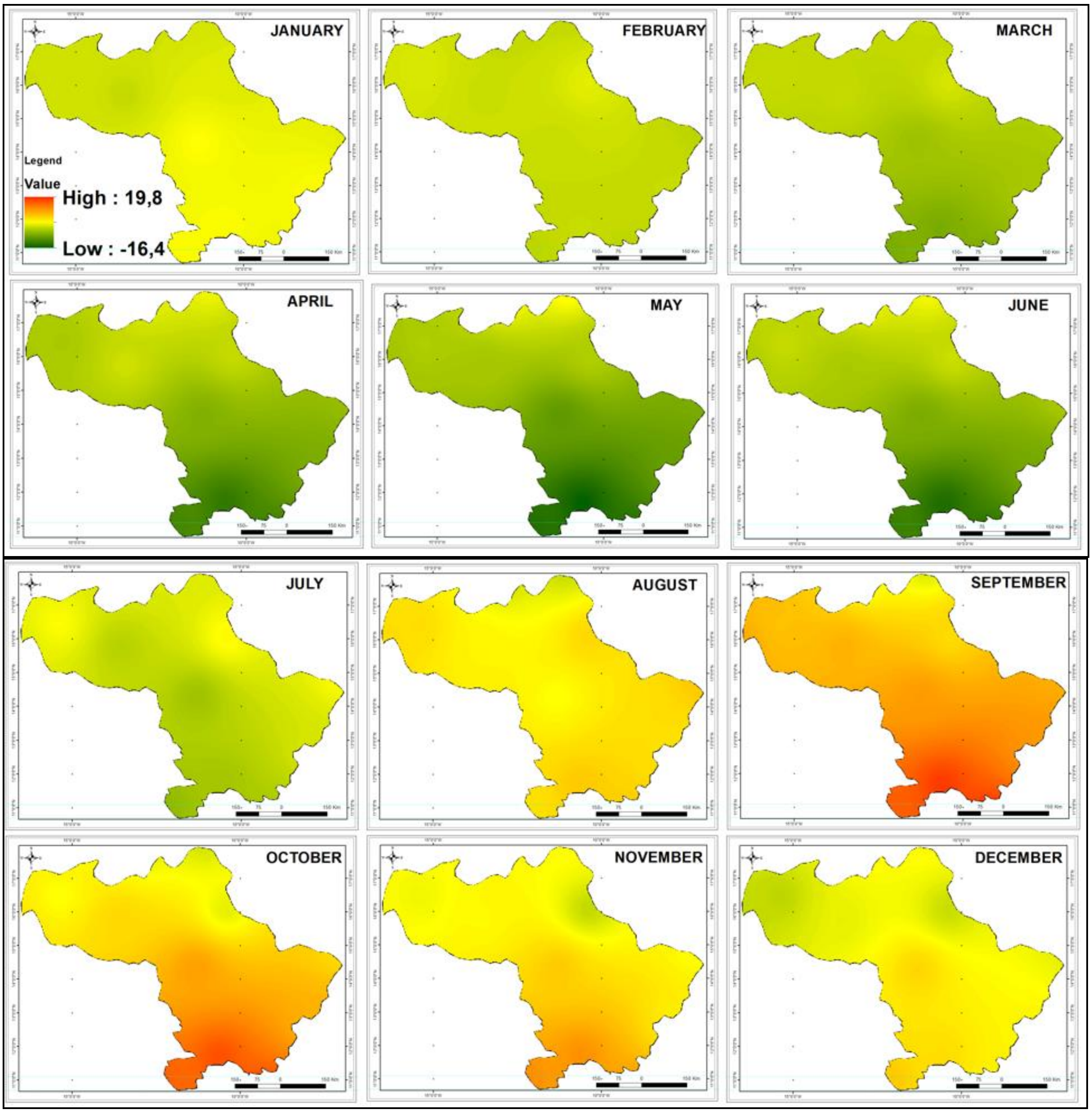


Figure 6. Monthly spatial variations of water depths (in cm) estimated from GRACE data for the entire Senegal River Basin by periods from 2003 to 2020.
Source: CNES / GRGS and OMVS, 2020

Nevertheless, some sites record unusual anomalies in the dry phase as was the case of the sites of Brakna in the months of April (1.00 cm), May (2.20 cm) and June (1,14 cm), of Hodh El Gharbi in the months of February (0.04 cm) and July (2.15 cm), of Saint Louis (0.13) and Dagana (1.59) in the month of July. Similarly, sites record negative anomalies on the wet phase as was the case of Brakna sites in August (-1.86 cm), September (-0.31 cm), October (-0, 60 cm) and January (-1.43 cm), of Hodh El Gharbi in the months of November (-2.10 cm), December (-1.77 cm) and January (-0.24 cm), of Tagant in the months of August (-1.73 cm), September (-0.49 cm) and October (-1.02 cm), Koulikore for the months of December (0.35 cm) and January (-0.25 cm).

The most significant negative monthly anomalies are noted at the sites in Guinea and Mali (which are the most watered parts of the basin), while the weakest are noted in the Senegalese and Mauritanian parts of the basin (the less devoid of rain). On seasonal time scales, GRACE-based groundwater storage troughs occur during the dry season, from January to July. However, precipitation peaks in August (358.3 mm), slightly out of phase with changes in groundwater. Groundwater storage is at its peak, one month after rainfall, in September (18.37 cm at Dinguiraye, 19.83 cm at Kankan, 15.75 cm at Labé, 10.49 cm at Kayes, 10, 74 cm in Kita, 8.90 cm in Saint Louis). The storage, although surplus from August to December, decreases rapidly from October to May and recovers continuously from June, with the beginning of rain (142 mm) to the maximum. Recovery of water storage usually begins in August, when precipitation peaks, resulting in a delayed response of groundwater to precipitation [45].

5. DISCUSSION

The remote sensing approach for detecting, assessing and quantifying groundwater variability presented here provides a framework for identifying regional groundwater storage anomalies. The lack of in situ water observations hampers understanding of the cascading changes in storage caused by moisture changes that traverse the hydrological cycle and affect groundwater resources. On the other hand, remote sensing techniques are very promising for understanding hydrological changes [46] and allow for an assessment of groundwater variation, as shown by the results presented here. Our results document a correlation between GRACE-based storage anomalies and in situ drought indices, suggesting that our approach can effectively characterise groundwater drought.

Globally, inconsistent estimates and different estimates of use and availability are hindering previous global estimates of groundwater stress [47,48] assessment of the sustainability of groundwater. Although groundwater is the main source of water for agriculture [49], the importance of groundwater is increasing rapidly as storage serves as a source of water supply, and surface water becomes less reliable and unpredictable [50].

The results of this study, based on the evolution of the average water depths estimated from the GRACE data, highlight the obvious seasonal and interannual variations of the storage of terrestrial water in the Senegal River basin and show two phases: the first phase, from 2003 to 2009, marked by a decline in groundwater storage, the second phase, from 2013 to 2020, largely surplus in land water storage. Thus, the GRACE-based water storage trend shows a slight improvement in groundwater in the Senegal River Basin, which contradicts the work of Döll [47], Reager et al. [1] and Zhang et al. [10] who reported changes in terrestrial water storage marked by a decline. Our results also incorporate changes in groundwater resources as a function of human pressures and changes in groundwater storage related to climate and natural variability, as captured by GRACE, thus responding to challenges in assessing development objectives to achieve sustainability proposed by the United Nations [52].

In general, the GRACE data set could contribute to the characterisation of regional droughts by measuring water storage deficits and the size of drought-stricken areas; the duration and magnitude of these deficits may be new measures to quantify and monitor the severity of drought [17]. On the basis of this theory, the results of the comparison between the GRACE system and the SPI, SPEI and SFI indices in the Senegal River Basin also provided methods for monitoring the evolution of drought in Senegal. GRACE data can now be used as an appropriate indicator for analysing changes in groundwater levels and for monitoring drought patterns in most watersheds in Senegal. Our results capture integrated assessments of aquifer dynamics, providing a framework for future assessments of aquifer sustainability. All differences in behaviour between indices are noted and are related to the fact that these different drought indices are formulated using different algorithms and principles. The differences and inconsistencies observed in the results could also be attributed to the fundamental differences in the type of data used to calculate the various indices, as well as the different time scales used.

Although GRACE demonstrates the great potential for monitoring groundwater storage variations in many parts of the world, especially in large-scale regions and regions with rare hydro-meteorological sites, where it is impossible to support the traditional methods, based on rich site observations [10], the uncertainties associated with GRACE results are still very high and need to be carefully assessed [45]. First, given the polar orbit design of GRACE satellites and GRACE payload observational errors, there are systematic errors and random noise in GRACE resolutions. In itself, GRACE cannot dissociate the contributions of various hydrological repositories from monthly water storage estimates [53]. In addition, the average monthly water storage is not accurate enough for the short time series, which prompted Thomas et al. [17] to indicate that it is preferable to use time series of at least 30 years, making it difficult to estimate and evaluate droughts using water storage indices. In the space domain, the systematic error is represented by so-called "north-south bands". The greatest uncertainty concerns the storage of soil moisture. The errors mainly result from the SMS error, the GRACE measurement error, the processing error and the leak error. The GRACE observation error and the uncertainty of GRACE data processing related to different smoothing methods must be taken into account. In order to reduce these scratches, researchers have developed methods of detachment [54,55].

GRACE-based inland water storage anomalies are effective indicators of extreme hydrologic events. Compared to traditional methods of drought monitoring, GRACE data provide a new approach to characterise droughts. By providing a single source of information in ungauged basins for which there is no reliable observation of rainfall and flow, GRACE data provide spatially distributed information on drought-related parameters quickly and easily [10]. In addition, the GRACE satellite detects vertically integrated changes in water storage between the Earth's surface and the deepest aquifers, and can monitor groundwater and groundwater loss [56]. However, for light / moderate droughts, such as meteorological droughts caused by a lack of precipitation, GRACE satellites are generally less useful because the storage of surface water remains in normal conditions [57]. Zhangli et al. [58] therefore recommend that GRACE data be used to characterize large-scale droughts, prolonged and severe droughts. It is encouraging that the next generation GRACE monitoring mission, scheduled for launch in 2018, is underway and should increase the spatial resolution to 50,000 km^2 and the temporal resolution to the week or two weeks [59].

Higher resolutions are at the root of wider applications in terrestrial hydrological monitoring. In addition, the combination of GRACE data with associated hydrological models, using methods such as GRACE data assimilation [60], would be an ideal solution to improve hydrological assessment and lead to significant improvements in our understanding of droughts and their development [10].

6. CONCLUSIONS

GRACE satellites have provided considerable information for the field of hydrology, revealing information on large-scale depletion of groundwater. GRACE Satellite Gravimetry provides an important approach for estimating changes in land water storage in the Senegal River Basin. In this study, the regional depletion of groundwater between 2003 and 2012 and its enhancement between 2013 and 2020 was estimated from GRACE-derived groundwater storage data from 2003 to 2020. The estimate was compared to drought indices. On seasonal time scales, variations in groundwater respond to the combined effect of groundwater discharge in the dry season and recharge during the rainy season. On interannual time scales, changes in groundwater correspond to changes in precipitation. Based on GRACE-derived groundwater storage estimates, groundwater recharge is now noted as rainfall increases in the basin. Thus, the annual groundwater amplitude in the Senegal River basin is 6.87 cm with an increasing trend of around 0.3 mm/year from 2003 to 2020, which equates to a volume of 0,09 km^3/year on the total surface of the basin. This increase is related to the improvement of rainfall conditions in the area since the 2000s as indicated by the drought indices. Given GRACE's deepening of groundwater in the Senegal River Basin, more effective measures should be taken to quantify them, and new water-related activities, in addition to those already present, should be more widely introduced and developed respectively.

Overall, as the methodology described in this work reliably captured major drought events occurring over a large spatial area; thus, it can be an ideal substitute for large-scale regions and regions with rare hydro-meteorological sites, where traditional methods based on rich site observations are impossible to apply. In the future, research should focus on improving the methodology of terrestrial water storage indices and identifying drought severity levels to increase the accuracy and scope of this approach.

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Status and use of water supply and sewerage systems in the Northern Development Region of the Republic of Moldova

Petru Bacal*, **Ana Jeleapov**, **Daniela Burduja**
Institute of Ecology and Geography, Chisinau, 1 Academiei Street, MD-2028, Republic of Moldova;
pbacal16@gmail.com (P.B.); anajeleapov@gmail.com (A.J.); danavirlan3@gmail.com (D.B.)

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Abstract: Water is an important resource for evolution and development of the economy of the North Development Region of the Republic of Moldova. From its availability and facilities to supply depend over 909 thousands inhabitants or 25% of the country population. The most important water resources are surface water that are represented mainly by the Dniester and the Prut rivers situated at the borders of the pilot region as well as groundwater. Internal rivers are characterized by low flow and do not represent significant resources. Surface water resources lead to decrease for the last decades due to different factors including reservoirs impact as well as climate change. Development of water supply and especially water sewerage system is an important factor in order to assure people and industries with water and qualitative life. In this regard, plus to evaluation of water resources dynamics, the aim of the present research is to identify the regional and local assessment of the state and use of public water supply and sanitation systems in the mentioned region for the last decade (2010-2020). Thus, total volume of abstracted water for public water supply systems was, on average, 18,800,000 m^3. For the study period, the total volume of water delivered to the population increased by 1.8 times (4,100,000 m^3), including in rural areas by 4.5 times (by 2,600,000 m^3), and in urban areas, by only 35 % (1,600,000 m^3). As a result of the expansion of the aqueduct network, ≈½ (48%) of the population of region has access to public water supply systems, including 83% in urban areas and only 31% in rural areas. Despite the rapid expansion of public aqueducts, water consumption per capita is low and is only 71 l/day, including 84 l/day in urban areas and only 53 l/day in rural areas. Population access to the public sewerage systems is only 19%, including 55% in the urban areas and only 0.3% – in the rural areas. Slow expansion of the public sewerage systems is caused by higher costs compared to water supply systems, and most local public authorities do not consider them as a priority.

Key words: North Development Region of Moldova, water resources, water use, water supply and sewerage systems, regional and local analysis, climate changes.

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1. INTRODUCTION

At present, given the intensification of climate change and its effects as well as continuing increase of the needs in water resources for population and industries, the supply with qualitative water resources is the key public policy in most countries of the world, especially in those with water scarcity. For this purpose, the permanent evaluation of the available water resources and the particularities of their use represent one of the most requested directions of scientific research, of a great theoretical and applied value. In the Republic of Moldova, the most important water resources are surface water that are represented mainly by the Dniester and the Prut transboundary rivers situated at the borders of the country as well as groundwater, internal rivers representing only local importance. Even if the volumes of main river are considerable, their usage is limited due to different factors, including depletion of water resources, big distance from main rivers, decreasing water quality etc. Water supply and sewerage system

* Corresponding author: pbacal16@gmail.com; Tel.: +373-693-52-816

construction is of a high concern at present in the Republic of Moldova due to low assurance of people and industries with centralized water supply. In urban area, 83% from inhabitants have access to centralized water supply and 55% to centralized sewerage system. In rural area, the access of population to the public aqueducts is 48%, but access to the public sewerage systems is only 0.3%.

In different regions of the country situation with water supply and sewerage system and all its elements and characteristics differ. In this regard, the aim of the present research is to identify the regional and local assessment of the state and use of public water supply and sanitation systems in the North Development Region of the Republic of Moldova. The main objectives of this study are: 1) estimation of surface and groundwater resources; 2) assessment of the current state of the public water supply and sewerage systems and their main components; 3) estimation of the access of the urban and rural population to the public water supply and sewerage supply systems and the level of their use; 4) analysis of the volume of water delivered to population and other categories of beneficiaries of public water supply systems; 5) identification of the evolution trends of the public water supply and sewerage systems and their capacities of utilization; 6) identification of the current achievements and problems of mentioned systems operation and elaboration of recommendations for their development.

2. LITERATURE REVIEW

Worldwide scientific publications devoted to water resources are multiple. A big part of the studies is oriented to description and analysis of hydrological time series of different rivers in many countries, water availability [11,12] other part contains hydrological modelling [13], other part estimates human impact as well as climate change effect on waters [14]. Special effort is made by scientists in order to evaluate quality of water resources and a consequence to identify and apply the most effective methods to combat pollution and degradation of water resources [15].

From those 17 global development goals established by 2030 in the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015 [16] the 6th one is devoted to water "Ensure availability and sustainable management of water and sanitation for all". Thus, water as a main resource to maintain life on our planet is the object of special interest and extensive studies. In this regard, this valuable resource should be managed in a sustainable way in order to assure with water resources in a balanced way ecosystems, people and economic needs.

In the Republic of Moldova, research in the field of water resources was performed by a few scientists. Most famous of them are Lalikin N. [17], Melniciuc O. [18,19]. Lalikin N. dedicated his research to evaluation of water resources and their changes due to human impact, reservoirs characteristics, sediment transport process at national scale. Melniciuc O. expressed his wide experience in the field of hydrology by development of a large number of publications devoted to theory of flow generation, regional synthesis of hydrological characteristics, mathematical modelling, sediment transport evaluation, human impact on rivers, evaluation of floods and low flow etc. The quality of surface and groundwater is reported in the scientific publications coordinated by Sandu M. and Lozan R., also from the Institute of Ecology and Geography [20], as well as in the recent Report on the quality of water in the urban public aqueducts [21].

Through relevant publications in the field of water, important are national reports State of the environment in the Republic of Moldova [22], which present short analysis of water resources as well as tables with water flow dynamics and types of water flow components such as: natural, real, environmental and available at o certain temporal scale. A comprehensive study on the rivers of Moldova is presented in a special edition Water Resources [23], which contains methodological base for evaluation of hydrological characteristics, as well as an extensive analysis of the Republic of Moldova's rivers and their basins, also a special attention was paid to evaluation of hydrological regime and phases of every river subject to monitoring. Actual and impactful documents are management plans of the Danube-Prut and Black Sea River Basin District [24] and Dniester river basin district [3]. These documents are developed and approved in 2017 and 2018 in accordance with water frame Directive 2000/60/EC [25] and contain analysis of the basins and rivers, evaluation of water resources, human impact on water bodies as well as plan of measures in order to improve water status and potential.

Very few researches were developed for evaluation of water resources of the North Development Region of the Republic of Moldova. Only in the last years some articles on general analysis of hydrological characteristics of the main river in the North DR [6, p. 58-63, 8, p. 12-30]. Ensuring the wide access of the population of the Republic of Moldova to public water supply and sanitation systems is reflected in recent analytical studies coordinated by OECD [26-28] and EPIRB (Environmental Protection of International

River Basins) [24], national [29-30] and regional sectorial strategic documents [31], as well as in the scientific researches [32], including of the authors of this study [3-8,33].

3. STUDY AREA

The North Development Region (DR) of the Republic of Moldova includes 11 districts and Balti municipality [1,2]. The total area of RD Nord is 10,000 km^2, which represents 30% of the total area of the country. Actual population is 909,000 inhabitants (25%), including 128,000 inhabitants of Balti municipality [3]. The biggest part of the study region is located within the Răut River basin (the main right tributary of the Dniester River), including districts Donduseni, Soroca, Drochia, Floresti, Sangerei, as well as Balti city [4]. The western part of the region is located in the Prut river basin, including Briceni, Edinet and Glodeni districts and almost all territory of Falesti (80%), Rascani (60%) and Ocnita districts [5].

The Dniester and Prut rivers are the most important water resources, but their exploitation capacities are limited, especially those of the Dniester River. The rivers, especially small and medium-sized, are regulated by reservoirs, the presence of which has both positive effects (flood prevention, irrigation, fish farming, tourism) and negative effects, especially of environmental nature [6, p. 58-63].

Groundwater reserves are sufficient in most districts, except Glodeni, Briceni, Soroca and Ocnita, being influenced by the operation of the Dniester Hydropower Complex (upstream from the village of Naslavcea) on the Dniester river and Costești-Stanca Hydropower Complex – on the Prut River [7, p. 14-15]. The majority of districts and rural settlements are supplied from groundwater sources, but local water resources are insufficient and the water quality is non-conforming with standards. For households mainly used groundwater from the Badenian-Sarmatian aquifer complex with richer reserves [8, p. 18]. Water treatment plants operate on the main aqueducts from the Dniester and Prut rivers, as well as in the cities, which are supplied from groundwater sources. At the same time, in the absolute majority of rural settlements, water treatment is not performed according to the standards in force [9,10].

Water supply volume varies depending on the size of the districts and their urban centers, on the number of households and other categories of water users connected to public aqueducts, available water reserves and on the capacities of abstraction, treatment, transportation and use of water [7, p. 59].

4. METHODS AND DATA

A set of methods was used to assess the characteristics of the North RD water resources, among which the most important are: statistical methods, mathematical modelling, cartographic and analytical methods. Statistical methods are used to assess the temporal dynamics of hydro meteorological features that are subject to multiannual observations. Mathematical modelling is used to assess the quantitative characteristics of water resources of rivers that are not monitored. Analysis of hydrological characteristics was performed based on the national normative document "Determination of hydrological characteristics for the conditions of the Republic of Moldova. Normative in constructions CP D.01.05-2012" [34].

The cartographic methods based on GIS techniques are used for spatial representation of water resources, water supply and sewerage systems at local and regional levels. The analytical method was used for: a) to identify quantitative and qualitative aspects of public water supply and sewerage systems; b) diagnosis of situation of water use and elaboration of recommendations to prevent problematic situations in this field; c) definition of priority directions of activity optimization of water resources management at regional and local levels. SWOT analysis method is applied for identification of problems and opportunities regarding the state of water supply and sewerage systems.

The main informational and statistical support of this study included: 1) Hydrological yearbooks of State Hydro meteorological Service [35]; 2) State Water Cadastre [36]; 3) National Geospatial Data Fund [37]; 4) Reports of National Bureau of Statistics on public water supply and sewerages networks [38] and of population dynamics [39]; 5) Reports of Association „Moldova Apa-Canal"[40]; 6) Annual Reports of State Inspectorate for Environmental Protection [9-10]; National Ecological Fund [41].

5. RESULT AND DISCUTIONS

5.1. Water resources

5.1.1. Surface water resources

Large rivers

Although these are located on the eastern and western borders of the study region, the Dniester and Prut rivers form the most important water resources [8, p.12-17]. The increasing distance from them reduces the degree of access and leads to use of alternative sources, especially groundwater, which are usually exploited at higher operating costs [7, p. 15].

The Dniester River is the main river of the Republic of Moldova. Within the limits of the North RD, the Dniesterriver flow is monitored at Grushka station, and water level at Naslavcea, Unguri, Soroca, Sanatauca (Table 1). At Grushka station, average water flow is 305 m^3/s, water layer – 198 mm, and average water volume – 9.6 km^3.

Table 1. Hydrological characteristics of rivers within the North Development Region.

River	Hydrologic station	Period, years	Average water flow, m^3/s	Average water flow, $l/s\ km^2$	Water layer, mm	Average water volume, mil. m^3
Large rivers						
Dniester	Grushka	1968-2019	306	6.28	198	9647
Prut	Sirăuţi	1990-2019	72.1	7.82	247	2276
Prut	Costeşti-Stânca	1982-2017	76.0	6.44	203	2396
River from the Dniester River Basin						
Răuţ	Bălţi	1972-2017	1.46	1.36	42.75	46.17
Cubolta	Cubolta	1966-2017	1.65	1.90	60.0	52.14
Cainari	Sevirova	1954-2017	1.29	1.59	50.05	40.76
River from the Prut River Basin						
Vilia	Bălăşineşti	1953-2017	0.59	2.27	71.44	18.65
Draghiste	Trinca	1957-2017	0.45	1.99	62.85	14.14
Ciuhur	Bârlădeni	1974-2017	0.28	2.48	62.04	8.93
Căldăruşa	Cajba	1951-2014	0.14	1.76	55.40	4.40

Source: SHS. Hydrological Yearbooks [35]

Based on the analysis of multiannual flows hydrographs of the Dniester River for the period 1968-2020, it can be seen that the general trend of flows is decreasing. Periods with maximum values followed by periods with minimum flow values are also recorded. Thus, the highest runoff was monitored for: 1968-1982 and 1997-2010, the duration being 15 years. The average flow values for the first period are 354 m^3/s, and for the second - 342 m^3/s. Lower runoff were recorded for: 1983-1996 and 2011-2020, the duration of the first period being 13 years, and the flows being 250 m^3/s. (Figure 1). The maximum annual flows and volumes recorded are 550 m^3/s, 17.3 km^3 (1980), 459 m^3/s, 14.5 km^3 (1998), and the minimum - 174 m^3/s, 5.47 km^3 (1987) and 183 m^3/s and 5.78 km^3 (1990).

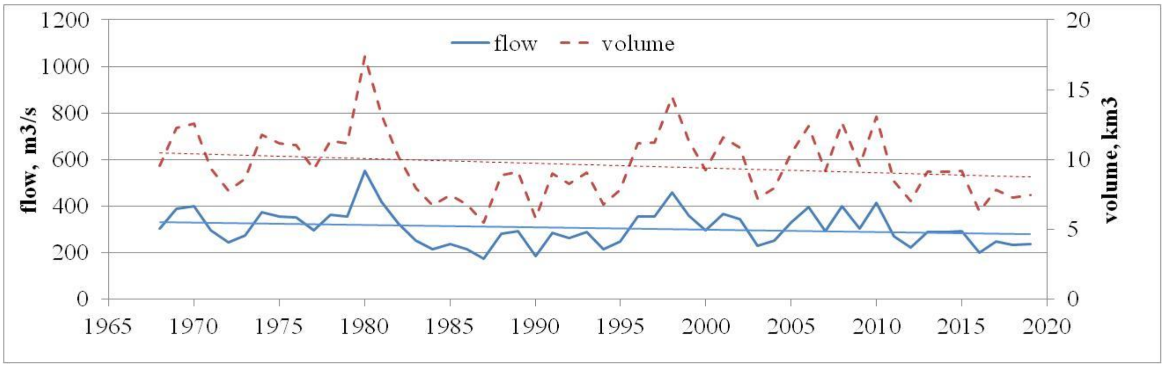

Figure 1. Multiannual flows hydrographs of the Dniester River, Grushka station.
Source: calculated by the author based on [35-36]

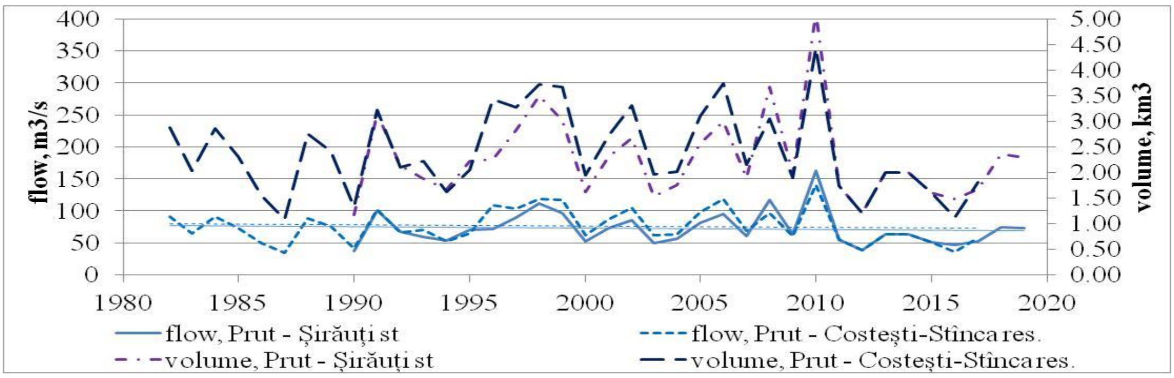

Figure 2. Multiannual flows hydrographs of the Prut River, Costeşti-Stânca reservoir station.
Source: calculated by the author based on [35-36]

The Prut River is an important water resource for the population and economic activities, it flows in the western part of the region. The flow of the Prut River is regulated by the Costești-Stânca reservoir, located in the middle course of the river [24]. Within the limits of North DR, the flow of the Prut river is monitored at the hydrological stations from Sirauti (Briceni district) and Costești, discharge from Costești-Stânca reservoir (Râșcani district), and the water level – at the stations from Lipcani, Dumeni and Braniște. At the hydrological station from Sirauti, flow is, on average, 72 m^3/s, layer – 247 mm, and volume – 2.3 km^3. At the Costești, flow is, on average, 76 m^3/s, layer – 203 mm, and volume - 2.4 km^3.

Analysing the evolution of the Prut river flow values, trends similar to those for the Dniester river can be observed. Thus, the period with lower flows lasts until 1996. During the years 1997-2010 there are high flow values, and during the years 2011-2020 – low water volumes (Figures 1 and 2). The highest annual flows and volumes were 141 m^3/s, 4.4 km^3 – in 2010, and 119 m^3/s, 3.74 km^3 – in 2006, and the lowest – 34.4 m^3/s, 1.09 km^3 in 1987, and, 35.6 m^3/s, 1.12 km^3 in 2016.

Water resources distribution during the year is non-uniform, being directly influenced by precipitation regime. As can be seen from the figures below, the most important water resources are generated in spring and summer, when maximum amounts of precipitation are recorded. During these seasons, about 60% of the total water volume of the Dniester River is formed. The month with the highest flows is April, during which 480 m^3/s are observed, followed by May-July, with flows of 370-400 m^3/s. The smallest volumes of water are specific for the autumn and winter seasons. About 20% of the water volumes are formed during mentioned season each, and at monthly level, the water flows are almost identical, varying in the limits of 214-260 m^3/s (Figures 3 and 4).

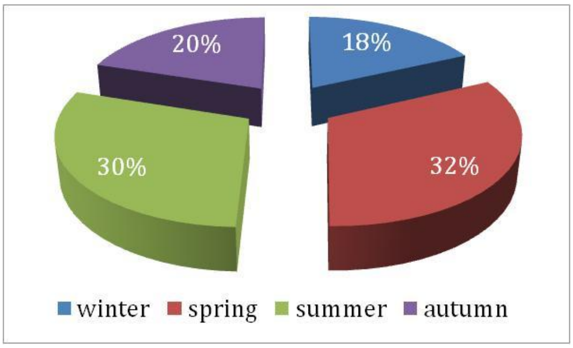

Figure 3. Seasonal distribution of the Dniester river flow, Grushka station [calculated based on 35-36].

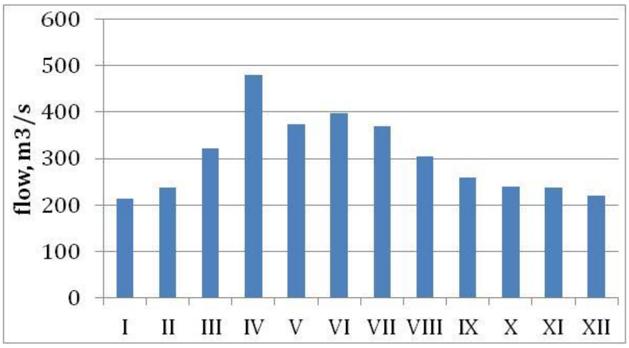

Figure 4. Monthly flows of the Dniester river, Grushka station [calculated based on 35-36].

The highest values of the Prut River flow are also formed in the spring and summer seasons, their share rising up to 70% (35% for each season). Flows during April-July reach values of over 100 m^3/s, and in the other months these gradually decrease up to ≈40 m^3/s in autumn and winter months (Figures 5 and 6).

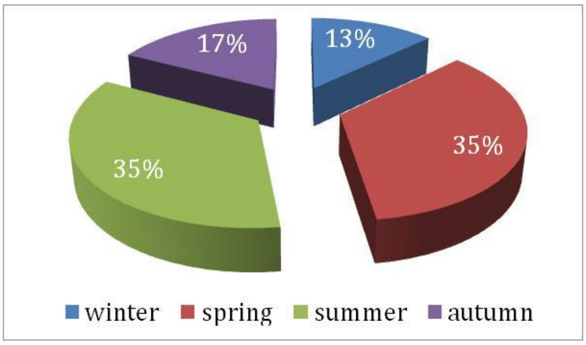

Figure 5. Seasonal distribution of the Prut river flow, Sirăuți station [calculated based on 35-36].

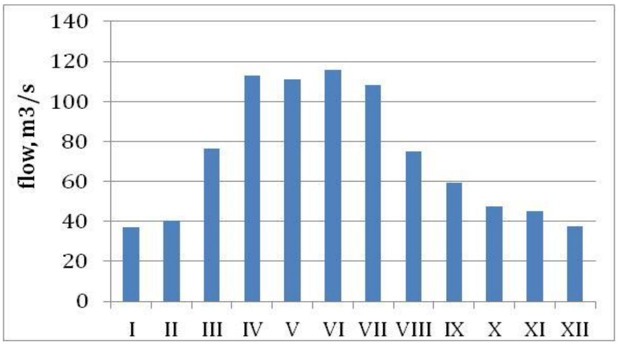

Figure 6. Monthly flows of the Prut river, Sirăuți station [calculated based on 35-36].

Small and medium-sized rivers

Small and medium-sized rivers represent important water resources at local level, which are formed largely within the boundaries of the North DR. The main small and medium-sized rivers are located in the Dniester river basin: Răut, Cubolta, Căinari, Ciulucul Mic, and in the Prut river basin: Camenca, Ciuhur, Racovăț, Vilia, Draghiște, Șovăț, etc. The highest flows are also specific to the rivers in the Dniester river basin (Table 1). The rivers Cubolta, Răuț and Căinari are characterized by flows equal to 1.3-1.5 m^3/s, layer – of 43-60 mm, and volume 41-52 mil.m^3. Flow dynamics show declining trends of Cubolta and Răut rivers flows.

The river flows from the Prut basin are lower, being about 0.14-0.60 m^3/s, and the volumes: of 4.4-19 mil. m^3, the layer being higher: 55-71 mm. Vilia and Draghiște have average flows of 0.59 and 0.45 m^3/s, and Ciuhur and Căldărușa – of 0.28 and 0.14 m^3/s, the specific flow is within the limits of 1.8-2.5 l/s km^2. The layer is 71 mm for Vilia, about 62 mm for Draghiște and Ciuhur and 55 mm for Căldărușa. The volumes are about 4,000,000 m^3 – for the Căldărușa river, 9,000,000 m^3 – for the Ciuhur river and 14,000,000-18,000,000 m^3 – for the Draghiște and Vilia rivers. The trends of rivers flow from the Prut river basin, in the case of the Vilia river are slightly increasing, and of the Draghiște, Ciuhur and Căldărușa rivers are decreasing.

Analysis of monthly flow of small and medium rivers shows that the most important water resources are also formed in the spring period followed by the summer. The smallest resources are formed in autumn and winter. Climate change in recent decades has led to a reduction in water resources, highlighting the months of March-July [22-23].

5.1.2. Groundwater resources

Most aquifers are composed of limestone and sandstone in the north, and more sand in the south. Direction of groundwater flow is in accordance with the geological structure. The oldest groundwater is found in the western and southwestern part of the country where the groundwater of the lower aquifers is captive, anaerobic and with a progressive salinity. Older aquifers are located in the eastern part of the study region [8, pp. 18-19].

Groundwater distribution of the *Vendian-Ripheric aquifer complex (V-R)* is in the eastern extremity of the region, in the Dniester river valley. The supply of this complex is made from the Podolia Plateau. The waters of this horizon are located at great depths, being difficult to access.

Groundwater within the *Cretaceous-Silurian aquifer complex (K2-S)* is spread over the entire territory of the North DR, except Sângerei district. The depth of groundwater varies between 104-3 m. The flow values are within the limits of 1.4-2.7 l/ sec, less often, of 0.1-0.3 l/sec. Mineralization ranges from 0.5 g/l to 1.0 g/l. According to the fluoride content, the groundwater of this complex does not comply with the quality standards and is not recommended for consumption by the population [20], but there are cases of their abstraction from wells and even from artesian wells.

Groundwater within the *Badenian-Sarmatian aquifer complex (N1b-S1)* is also spread over the entire North DR territory. The flow of the wells differs from one area to another, being in the limits of 0.1-2.2 l/sec (Dondușeni, Ocnița district) and 0.1-0.3 l/sec (Glodeni and Fălești districts). Groundwater mineralization varies from 0.5-1.0 g/l. The waters of the Badenian-Sarmatian aquifer complex largely comply with water quality standards and are widely used by public systems for the centralized supply of population with drinking water.

The *Alluvial-Deluvial aquifer horizon (aA3)* is specific to river floodplain. The waters of this horizon are extracted by population located in these areas from wells and springs. The thickness of the aquifers varies from 1 m to 30 m. The flow rates of the springs are from 0.01 l/sec to 1-2 l/sec. Mineralization varies from about 1 g/l to 10 g/l. Groundwater is fresh to slightly saline

5.2. Status and use of water abstracted systems

According to National Bureau of Statistics (NBS) [38], in the analysed period (2010-2020), the total volume of abstracted water for public water supply systems in the North DR was, on average, 18,800,000 m^3, including 16,200,000 m^3 or 87% in urban areas and 2,700,000 m^3 or 13% in rural areas (Figure 7).

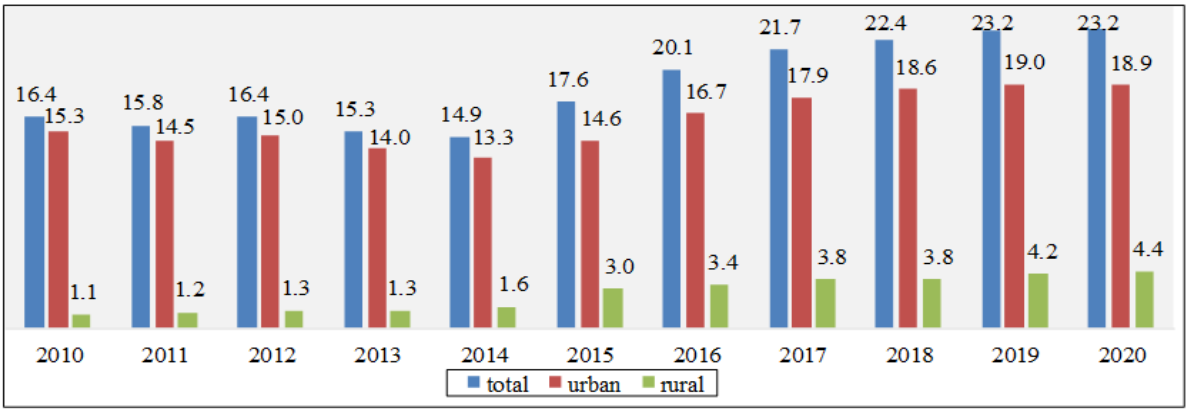

Figure 7. Dynamics of the total volume of abstracted water in the North RD, in mil. m^3.
Source: National Bureau of Statistics [38]

The maximum volume of abstracted water is registered in the districts of Soroca (11,300,000 m³) and Edinet (1,700,000 m³), where are located the main water pumping stations in the Dniester and Prut rivers, as well as in the districts of Drochia (937,000 m³), Florești (948,000 m³) and Sângerei (≈800,000 m³), with an average level of urbanization and with more extensive functional aqueducts in urban and rural areas. The minimum volume of captured water is registered in the districts of Ocnița (227,000 m³) and Briceni (538,000 m³), with smaller dimensions and urban centers and with less access to rural public aqueducts. The urban space predominates absolutely not only in Bălți municipality, but also in Edineț (88%), Drochia (75%) and Fălești (74%) districts, with urban centers of average sizes and a higher level of industrialization, as well as in the districts of Ocnița (100%) and Soroca (100%), with a very low level of access of the rural population to public aqueducts [7, p. 57].

In the urban area, the total volume of captured water increased by 3,500,000 m³ (from 15,300,000 m³ to 18,900,000 m³) or by 23% (Figure 7). This dynamic is predominantly conditioned by the similar evolution of the volume of abstracted water by SE Acva Nord from Soroca, which contributes about 60% of the delivered water to public aqueducts in the North DR and with 70% to urban public aqueducts in this region. At the same time, the abstracted water by SE Acva Nord is delivered, almost exclusively, in the municipalities of Bălți and Soroca, and the water distribution capacities are insufficiently exploited.

The total volume of abstracted water from surface sources were, on average, 13,100,000 m³ or about 70% of the total volume of water captured in the North RD, which is due, almost exclusively, to the pumping stations of the water supply companies SE Acva Nord from Soroca (11,300,000 m³) and from the Edineț city (1,500,000 m³). In the rest districts, the absolute majority of waters, especially in rural areas, are captured from underground sources.

During the analyzed period, the total volume of water captured from surface sources in the North DR increased by ≈1/4 or by about 4,000,000 m³ (from 12,100,00 m³ in 2010 to 16,200,000 m³ in 2019) (Figure 8). The respective dynamics is predominantly conditioned by the similar evolution of the respective indicator at SE Acva Nord Soroca, which registers an increase of 1.5 times or by 4,500,000 m³.

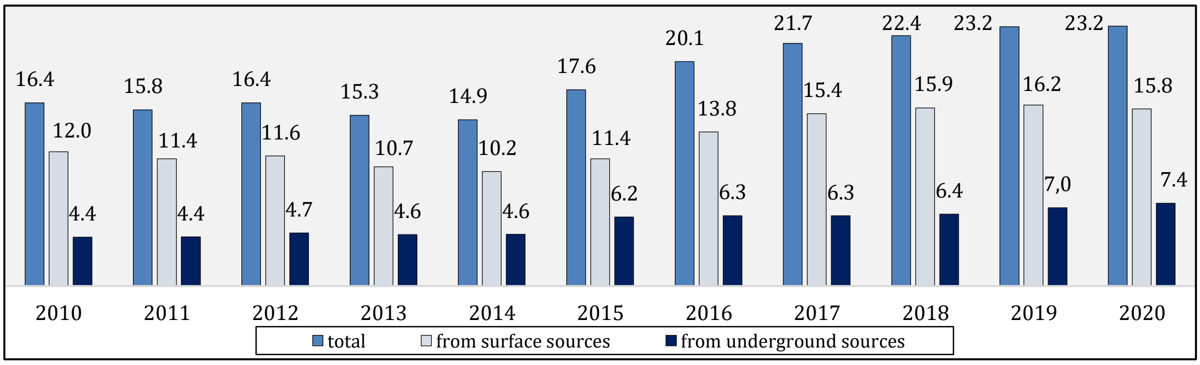

Figure 8. Dynamics of the abstracted water volume in the North RD by sources of origin, in mil. m³.
Source: National Bureau of Statistics [38]

Also, the insignificant increase of the volume of water captured from surface sources is registered in Fălești, Florești and Sângerei districts, as a result of the connection of some rural localities to the main aqueducts Prut-Fălești and Soroca-Bălți-Sângerei. At the same time, there is a significant reduction in the volume of captured water from surface sources in the Glodeni town (by 3.0 times), due to the bankruptcy of the sugar factory and in the Edinet town, due to the reduction of domestic and industrial consumption.

The total volume of water captured from underground sources in the North DR increased by ≈1.7 times or with about 3,000,000 m³ (Figure 8). The positive dynamics is entirely due to the multiple increases (by 4.0 times or with 3.1 million m³) of the volume of captured water from underground sources in rural areas. In the urban space there is an oscillating evolution against the background of a general trend of weak reduction. The maximum increase is found in the districts of Edineț (2.2 times) and Soroca, where previously the public aqueducts were supplied, almost exclusively, from surface sources.

In the North RD, water is supplied by about 350 pumping stations, of which about 230 stations are located in rural areas [38]. The pumping stations, which distribute the water for domestic use captured from the banks of the Dniester and Prut rivers, serve the main aqueducts Soroca-Bălți-Sângerei, Prut-Edineț, Prut-Glodeni and Prut-Fălești, with their branches. At the same time, are used only about ¼ of the design capacities of the existing stations, which is explained by their advanced degree of wear.

According to data from the Inspectorate for Environmental Protection (IEP), in the region there are 1382 artesian wells, of which only 38% are exploited. The high share of unexploited artesian wells is caused by advanced wear, by the insufficient financial capacity of LPAs for this purpose, but also by their incorrect location. Despite the mentioned technical deficiencies, the production capacity of the existing catchment facilities is sufficient to cover the current water need of 22,000 m³/day [31, p. 17].

The water treatment plants operate at the main mentioned aqueducts for the distribution of water captured from the Dniester and Prut rivers. At the same time, in the absolute majority of rural localities, which capture water from underground sources, water is not treated according to the regulations in force, and chlorination is insufficient and random. Therefore, water delivered to rural consumers often does not comply with sanitary regulations, especially the hardness and fluoride content [31, p. 22]. Water quality monitoring systems exist only in the urban areas, and episodic tests are performed by the laboratories of the Center for Public Health and the Center of Ecological Research from Bălți city.

5.3. Public water supply systems

In the 2010-2020 years, the number of public water supply systems in the North DR increased by 2.3 times or from 127 units to 299 units (Figure 9), of which 267 systems (91%) are operational. The positive dynamics is registered in all districts of the region, including Fălești (from 3 to 30 units), Soroca (by 5.5 times), Râșcani (by 4.9 times) and Edineț (by 4.8 times), Dondușeni districts (by 3.7 times).

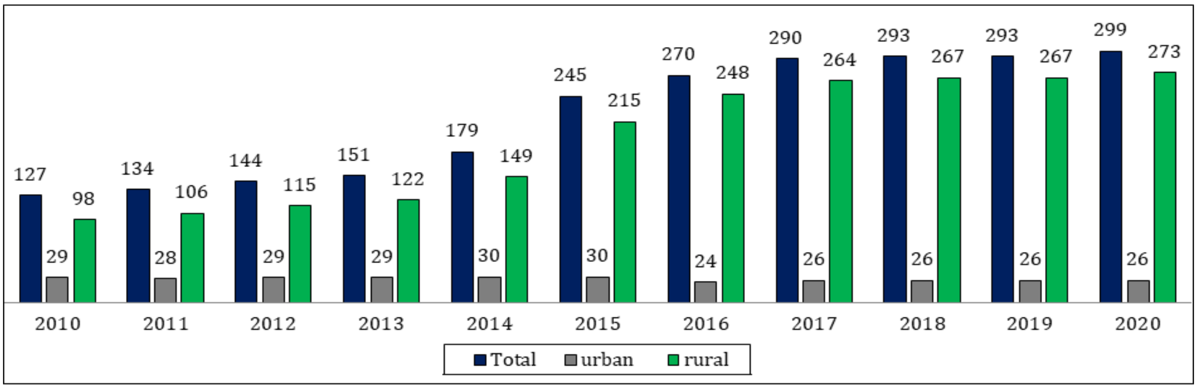

Figure 9. Dynamics of the number of public water supply systems, units.
Source: National Bureau of Statistics [38]

In the 2020 year, in the North DR were registered 299 public water supply systems, including 273 systems (88%) in rural areas and 26 systems (12%) in urban areas. The maximum number of public water supply systems is attested in the districts of Sângerei (49), Florești (48) and Râșcani (44), which are also characterized by a maximum access of the population to public aqueducts, especially in rural areas (Table 2). The highest growth rates are in the 2013-2016 years, due to the allocation of planned financial support from the National Ecological Fund [41] in order to achieve the objectives of the Water Supply and Sanitation Strategy [29], the National Program for the implementation of the Protocol on Water and Health (2016-2025) [30], the Regional Sectorial Program for water supply and sanitation [31]. Overall, the number of rural public aqueducts increased 2.7 times (from 98 to 267 units). At the same time, in urban areas, the number of public water supply systems decreased by 3 units (10%).

Table 2. Status and access of public water supply systems in the districts of North RD (year 2020).

	Districts	**Number of systems**			**Length of public aqueducts**, in km			**Number of connected population**, in thousand			**Access of the population to public aqueducts**, in %		
		total	urban	rural	total	urban	rural	total	urban	rural	total	urban	rural
1	Briceni	25	4	21	214	77.7	136	17.8	9.2	8.6	24	70	14
2	Ocniţa	3	3	0	63.7	63.7	0	8.1	8.1	0	16	45	0
3	Edineţ	24	3	21	244	121	122	28.6	17.1	11.5	37	67	22
4	Donduşeni	11	2	9	107	43.0	63,8	11.1	4.7	6.4	27	52	20
5	Soroca	17	2	15	398	175	211	42.9	31,8	11,2	46	91	19
6	Drochia	21	1	20	389	70,5	318	32.5	14,2	18,3	40	83	29
7	Floreşti	48	3	45	536	125	412	40,7	16,1	24,6	50	96	38
8	Sângerei	49	3	46	452	67.7	384	46.8	14.5	32.3	56	91	48
9	Râşcani	44	2	42	461	60.6	400	44.9	13.6	31.3	72	*97*	63
10	Glodeni	25	1	24	276	58.6	217	23.9	8.5	15.4	44	87	34
11	Făleşti	30	1	29	378	47.2	331	37.8	15.7	22.1	45	*99*	32
12	Bălţi	2	1	1	258	244	14.3	105	104	1.0	82	85	20
	North DR	**299**	**26**	**273**	**3,776**	**1,154**	**2,622**	**440**	**257**	**183**	**48**	**83**	**31**

Source: National Bureau of Statistics [38]

The total length of public aqueducts is ≈3,800 km, including 2,600 km (69%) in the rural areas and 1,200 km (31%) – in the urban areas (Table 2). During the 2010-2020 years this indicator increased by 2.1 times or with ≈2.0 ths km, including in rural areas – by 4.0 times (figure 10). In the urban space, there is an oscillating evolution, against the background of a negative dynamic in recent years, including Bălți municipality, Glodeni and Florești districts, being caused by the disconnection of industrial enterprises from the public water supply system.

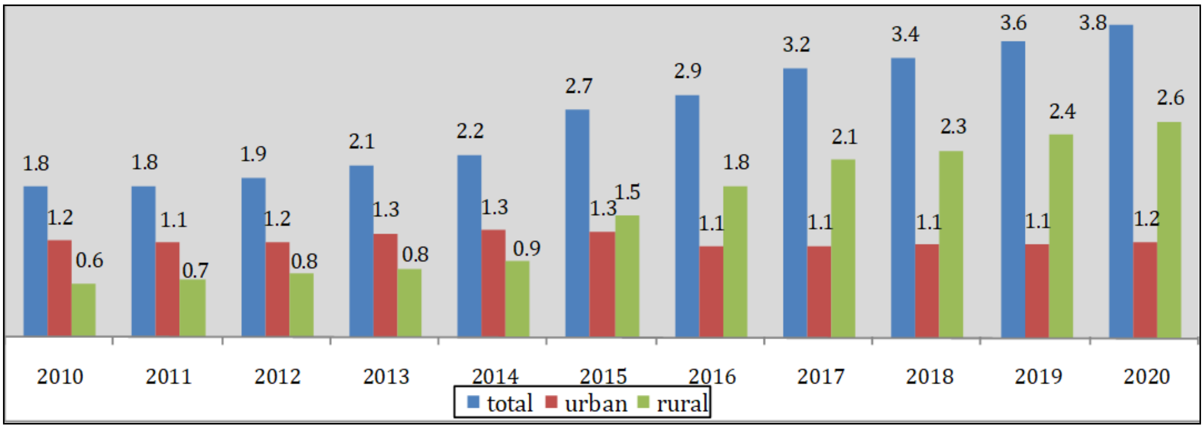

Figure 10. Dynamics of the length of public water supply systems in the North DR, in thousands km.
Source: National Bureau of Statistics [38]

The most extensive aqueducts are in the districts of Florești (536 km), Râșcani (461 km), Sângerei (452 km), Soroca (398 km) and Fălești (378 km), with a larger number of localities connected to public aqueducts (Figure 11). The minimum length of the aqueducts is also found in the districts of Ocnița (63.7 km) and Dondușeni (107 km) with smaller dimensions and a small number of localities connected to public aqueducts. The most extensive urban public aqueducts are in the municipalities of Bălți (258 km), Soroca (149 km) and Edineț (85.2 km), as well as in the Florești (93.6 km) and Drochia towns (70.5 km).

In the rural areas, water distributed by public water supply systems is used also for irrigation or frequent washing of transport units, which poses increased risks in the operation of those systems, especially water shortages in the droughts periods, insufficient of pressure, increasing of unauthorized use of water from the system etc [24,33].

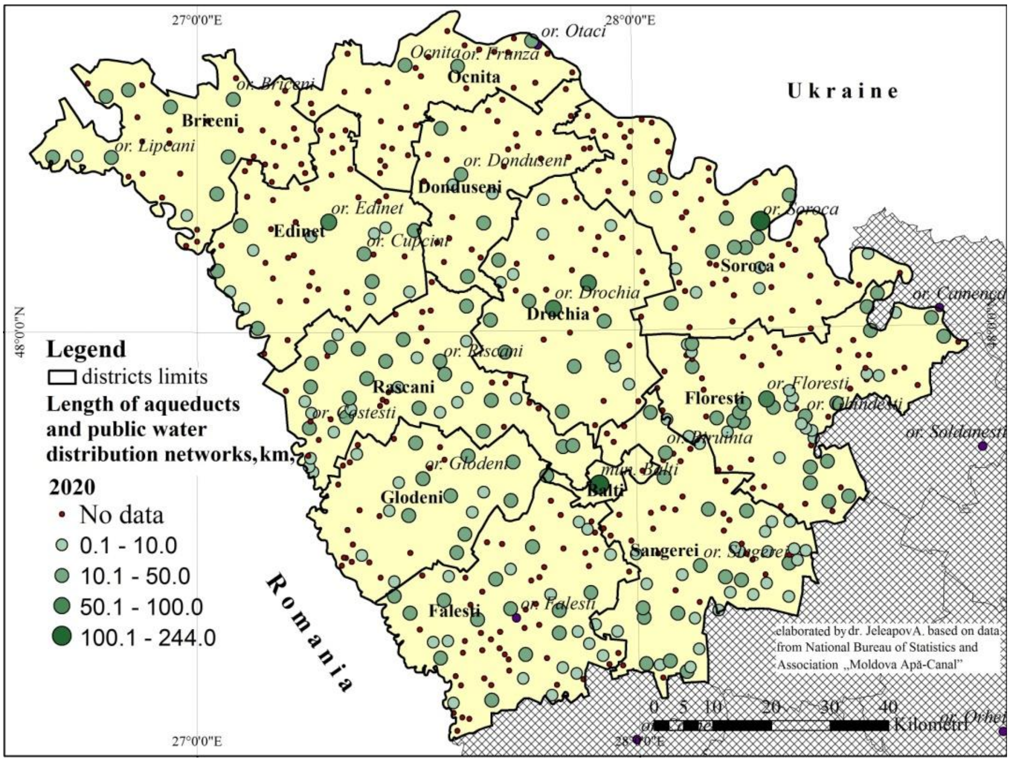

Figure 11. Length of public aqueducts in the localities of the North DR, in km, year 2020.
Source: National Bureau of Statistics [38]

As a result of the expansion of the aqueduct network, ≈½ (48%) of the population of the North DR has access to public water supply systems, including 83% in urban areas and only 31% in rural areas (Table 2). The maximum access of the population to public aqueducts is attested in Bălţi municipality (82%), in Râșcani districts (72%), Sângerei (56%) and Florești (50%), and the minimum access in Ocnița districts (16%), Briceni (24%) and Dondușeni (27%).

5.4. The volume of used water delivered by public water supply systems

In the analyzed period (2010-2020), the total volume of water supplied by the public water supply systems registers an ascending dynamic, both in the rural and in the urban areas. Overall, the volume of used water increased 1.5 times, including in the urban areas, by 34% (from 15,100,000 m^3 to 20,200,000 m^3), and in the rural areas – by 3.6 times (from 983,000 m^3 to 3,500,000 m^3) (Figure 12).

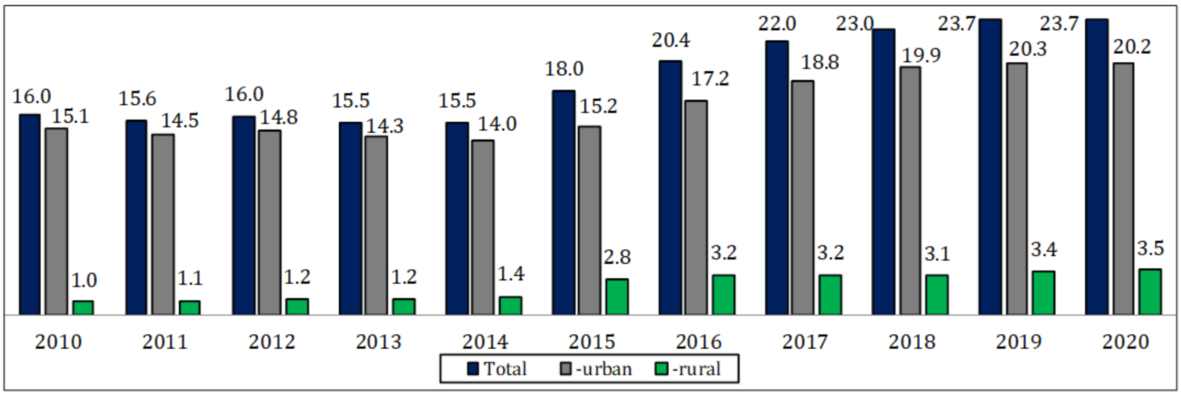

Figure 12. Dynamics of the total volume of water delivered by public water supply systems (mil. m3). Source: National Bureau of Statistics [38].

The multiple increases in the volume of water delivered by public aqueducts are attested in the districts of Dondușeni (by 5.2 times until 2019), Drochia (by 3.3 times), Râșcani (by 3.2 times), Fălești (by 2.4 times) and Sângerei (by 2.1 times). The reduction (by ≈2 times) of the volume of water delivered is registered only in the Glodeni district, which is due to the cessation of the activity of the sugar factory from Glodeni town, which supplied water to this city. Given the declining of population, with the exception of attractive suburban areas, water consumption will be reduced and some of the newly built aqueducts will become dysfunctional. At the same time, the multiple conveniences of centralized water supply, especially in suburban communes with various economic opportunities, will increase water consumption.
The volume of supplied water varies depending on the size of the districts and their urban centers, by the number and size of public aqueducts, by the number of connected people, by the number and consumption of water of enterprises and organizations connected to public aqueducts, by water reserves [4-5] and their technical and financial capacity to operate. Due to high water losses, only ½ of the abstracted water is delivered to consumers [31, p.20].

Table 3. Volume of delivered water by public aqueducts in the districts and cities of the North DR, in thousand m^3 (2020 year).

	Districts	**Categories of water users**												**Water consumption per capita**, litres/day		
		Total			Households			Budget organization			Other categories					
		total	urban	rural	total	urban	rural	total	urban	rural	total	urban	rural	total	urban	rural
1	Briceni	357	195	163	320	175	145	25.9	11.3	14.6	11.6	8.4	3.2	55	58	52
2	Ocniţa	168	168	0	144	144	0	18.5	18.5	0	4.7	4.7	0	57	57	...
3	Edineţ	605	314	291	545	264	281	24.1	14.5	9.7	35.8	35.8	0	58	50	69
4	Donduşeni	213	105	108	186	94	92	17.9	5.2	12.7	8.5	5.7	2.8	52	61	46
5	Soroca	13,335	13,144	191	846	662	184	92.5	86.4	6.2	12,397	12,395	1.2	66	73	47
6	Drochia	988	395	593	920	360	560	38.2	17.3	20.9	25.3	18.0	7.3	83	76	89
7	Floreşti	873	396	477	768	346	422	37.7	25.2	12.4	67.7	25.6	42.1	59	68	53
8	Sângerei	808	308	500	743	276	467	45.3	19.4	25.9	19.1	12	7.1	47	58	42
9	Râşcani	852	274	578	785	249	535	40.5	13.4	27.1	27.2	11.6	15.6	52	55	51
10	Glodeni	438	159	280	404	140	263	25.6	15.1	10.5	9.4	3.1	6.3	50	51	50
11	Făleşti	650	315	335	600	284	316	19.8	9.3	10.5	30.4	21.7	8.7	47	55	41
12	Bălţi	4451	4427	24	3260	3238	21,8	230	229	0.2	961	959	2.4	116	117	69
North DR		**23,738**	**20,199**	**3,539**	**9,520**	**6,233**	**3,287**	**616**	**465**	**151**	**13,598**	**13,501**	**96.7**	**71**	**84**	**53**

Source: National Bureau of Statistics [38]

In 2020 year, the total volume of water supplied by public aqueducts in the North DR was 23.7 million m^3, including 12,700,000 m^3 of water delivered by the company Acva Nord Soroca and 10,800,000 m^3 delivered by the operators of the public water supply services from the districts of the region and from the municipality of Bălți (Table 3). Large volumes of water are delivered in the municipality of Bălți (4,500,000 m^3), as well as in the districts of Soroca and Drochia (1,000,000 m^3 each), Florești (873,000 m^3), Râșcani (852,000 m^3) and Sângerei (808,000 m^3). The minimum volume of water was delivered in the smaller districts and with a low level of access to public aqueducts – Ocnița (168,000 m^3), Dondușeni (213,000 m^3), Briceni (357,000 m^3) and Glodeni (438,000 m^3).

Despite much faster extension of the rural aqueducts, ≈90% of the total volume of water supplied is delivered by urban municipal enterprises. In the urban area, the maximum volume of water is also delivered in the cities of Soroca (850,000 m^3), Drochia (395,000 m^3) and Florești (330,000 m^3), and the minimum volume – in the small towns such as Lipcani (33,900 m^3), Mărculești (25,000 m^3) and Ghindești (40,900 m^3) from Florești district, Costești from Râșcani district (43,400 m^3), Biruința from Sângerei district (47,000 m^3) and Otaci from Ocnița district (71,000 m^3). The urban space predominates in Bălți municipality (≈100%), as well as in Ocnița (100%), Soroca (≈100%), Briceni (54%) and Edineț (52%) districts (Figure 13). In the rest districts, the rural area predominates, including in the districts of Râșcani (68%), Glodeni (64%), Sângerei (62%), Drochia (60%), Florești (55%) and Fălești (52%).

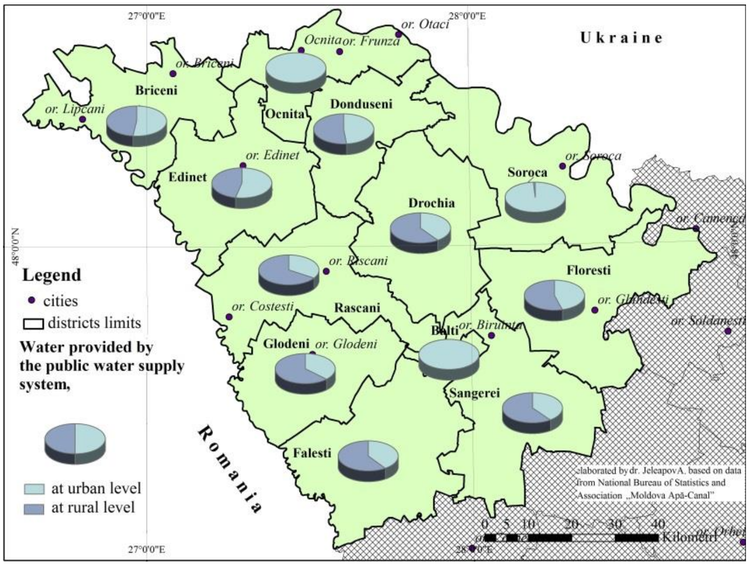

Figure 13. The share of urban and rural areas in the total volume of water provided by public water supply systems in the districts of RD Nord and Bălți municipality (year 2020).
Source: National Bureau of Statistics [38]

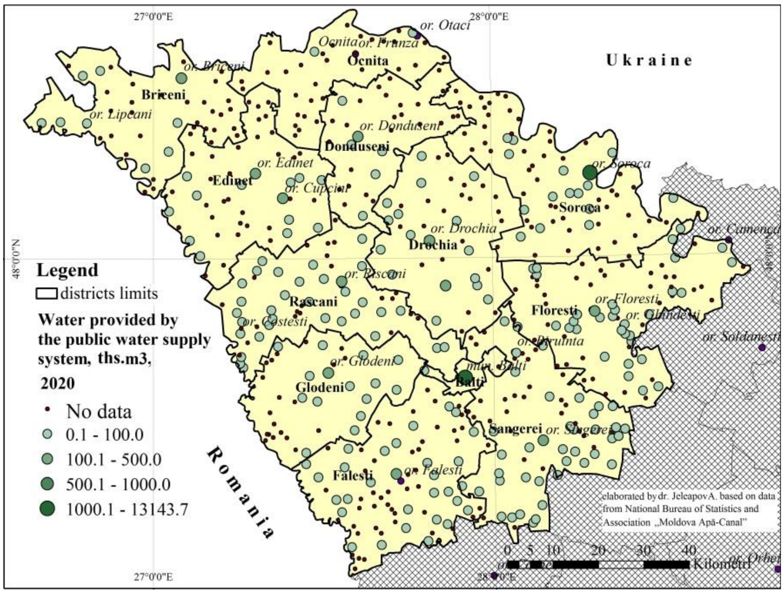

Figure 14. Total volume of water delivered by water supply systems in the localities from the North DR, in ths m^3.
Source: National Bureau of Statistics [38]

In the rural areas, the maximum volume of water are provided in the villages with larger aqueducts (Figure 14), including: Larga (53,000 m^3) from Briceni district; Bădragii Vechi (80,200 m^3) and Brătușeni (63,300 m^3) from Edineț district; Sofia (182,000 m^3), Nicoreni (77,000 m^3), Țarigrad (72,200 m^3), Pelinia (55,000 m^3) and Chetrosu (52,000 m^3) from Drochia district; Prodănești (70,000 m^3), Gura Camencii (46,000 m^3) and Vărvăreuca (44,000 m^3) from Florești district; Sărata Veche (39,000 m^3) from Fălești district; Iabloana (63,000 m^3) from Glodeni district; Corlăteni (88,000 m^3), Zăicani (65,000 m^3), Nihoreni (52,000 m^3) and Mihăileni (45,000 m^3) from Râșcani district; Pepeni (73,000 m^3), Chișcăreni (52,000 m^3), Heciul Nou (41,000 m^3) from Sângerei district; Rublenița (43,000 m^3) from Soroca district (Figure 14).

In the urban space were delivered, on average, 5,300,000 m^3 of water or ≈¾ of the total volume (Table 3). As a result of the concentration of industrial enterprises in cities, the share of the volume of water supplied to the population in rural areas is higher compared to urban areas and constitutes about 90% in the absolute majority of the districts of the study region.

Overall, the dynamics of the volume of water supplied to the households (populations) is similarly to that of the total volume of water delivered by public aqueducts, but the positive trend is more pronounced and is observed in all districts and Bălți municipality. Thus, the total volume of water supplied to the population increased by 1.8 times or from 5,300,000 m^3 in 2010 to 9,500,000 m^3 in 2020. In rural areas, the volume of water supplied to the population increased by 4.5 times (from 727,000 m^3 to 3,300,000 m^3), and in urban areas, with only 35% (from 4,600,000 m^3 to 6,200,000 m^3). As a result, the share of the rural space in the total volume of water supplied to the households of the North DR increased by more than 20 percentage points (p.p.) or from 14% to 35%. The multiple increase of the volume of water delivered to the households is observed in the districts of Drochia (by 3.4 times), Rășcani (by 3.3 times), Fălești (by 3.2 times), Sângerei (by 2.3 times), Florești (by 2.2 times) and Edineț (by 2.0 times), which is due, almost exclusively, to the multiple increase of this indicator in the rural localities.

In 2020 year, to the households was delivered 9,500,000 m^3 or about 80% of the total volume (without water delivered by SE Acva Nord). This proportion is similar in all districts and cities of the region, except Balti municipality, with a higher share of industrial and transport enterprises, and the volume of water delivered to the households determines the total volume [7, p. 68-69]. In the urban areas were delivered 6,200,000 m^3 (65%) of water and 3,300,000 m^3 (35%) in the rural areas. The maximum volume of water delivered to the householders (Table 3) is attested in Bălți municipality – 3,200,000 m^3 (40%), as well as in the districts of Drochia (920,000 m^3), Soroca (846,000 m^3), Râșcani (785,000 m^3), Florești (768,000 m^3) and Sângerei (743,000 m^3), and the minimum volume – in the small districts with a low level of access to public aqueducts, including Ocnița (144,000 m^3) and Dondușeni (186,000 m^3).

In the urban space, the maximum volume of water is also delivered in the Bălți city (3,200,000 m^3), as well as in the town of Soroca (662,000 m^3), Drochia (320,000 m^3), Florești and Fălești (about 280,000 m^3 each), and the minimum volume – in the smaller towns, such as Lipcani (29,900 m^3), Mărculești (20,100 m^3) and Ghindești (39,800 m^3) in Florești district, Costești in Râșcani district (40,100 m^3), Biruința from Sângerei district (41,400 m^3), Cupcini (75,400 m^3) from Edineț district; Ocnița and Otaci from Ocnița district (69,000 m^3). The maximum volume of water delivered to the rural population is attested in the districts of Drochia (560,000 m^3), Râșcani (535,000 m^3), Sângerei (467,000 m^3) and Florești (422,000 m^3), which have a higher level of access to available sources of water (Table 3). The minimum volume of water use is registered in the smaller districts and/or with less access to aqueducts, including the districts of Ocnița (0 m^3), Soroca (184,000 m^3) and Briceni (145,000 m^3).

The volume of water delivered to other categories of consumers was, on average, 11,000,000 m^3 (58%), and in 2020 – 13,600,000 m^3 (57%), of which 12,700,000 m^3 (90%) delivered by SE Acva Nord Soroca to the operators and enterprises from Bălți municipality and from the localities related to the Soroca-Bălți main aqueduct, as well as its extensions to the cities of Sângerei and Râșcani.

For industrial and services enterprises connected to local public aqueducts were delivered ≈1,400,000 m^3 (13%), of which over 90% (1,200,000 m^3) – in the urban area, where are concentrated most of industrial and service enterprises. The volume of water delivered to these categories of water consumers is conditioned by the number and production capacity of enterprises, which do not have their own sources of water supply [7, p. 72]. Therefore, the maximum volume of water delivered to enterprises is observed in the cities of Bălți (959,000 m^3), Soroca (100,000 m^3) and Edineț (130,000 m^3).

For budget organizations, was delivered, an average 733,000 m^3 of water or ≈7% of the total volume, including 484,000 m^3 (66%) in urban areas (Table 3). Unlike industrial enterprises, budget organizations, especially educational insurance and public administration, are widespread in rural areas. Among the budgetary organizations we mention the hospitals from Bălți municipality and from the district centers, the educational and administrative centers, which are widespread as well in rural areas. The maximum volume of water delivered to budget organizations is recorded in larger cities, including Bălți (254,000 m^3), Soroca (86,400 m^3), Florești (24,000 m^3) and Edineț (21,000 m^3).

Despite the rapid expansion of water supply networks, water consumption per capita is low and is only 71 liters/day, including 84 liters/day in urban areas and 53 liters/day in rural areas (Table 3) or twice, less than the norm of water consumption for the population. Water consumption is directly conditioned by both the number of connected population and the amount of local water resources [33]. Thus, the maximum water consumption per capita is observed in Bălți municipality (116 l/day), as well as in the districts of Dondușeni (130 l/day in 2019) and Drochia (88 l/day), and the minimum consumption – <50 liters/day is attested in Fălești and Sângerei districts with limited groundwater reserves.

5.5. Public wastewater treatment and purification systems

There are only 52 public sewerage systems in the North RD or ≈6 times less than the public water supply systems (Tables 4). The number of sewerage systems in urban areas is identical to that in rural areas, but the capacity for receiving and treating wastewater is much higher. Also, in Glodeni and Florești districts, the large number of public sewerage systems is explained by the fact that small systems have been registered, which include several public institutions (kindergartens, schools) and households around them. Maximum number of public sewerages systems is registered in the districts of Florești (12), Râșcani (6), Edineț and Dondușeni (5 each).

Table 4. Status of public wastewater disposal and purification systems in the North DR (2020).

Districts	Number of public sewerage systems			Length of sewerage network, in km		Access to the public sewerage systems, in %			Number of treatment plants			Capacity of treatment plants, m³/day	
	Total	urban	rural	Total	urban	Total	urban	Rural	Total	urban	rural	Total	urban
Briceni	3	3	0	31.4	31.4	6.8	37	0	1	1	0	1,200	1,200
Ocnița	4	4	0	18.2	18.2	9.3	27	0	3	3	0	217	217
Edineț	5	3	2	55.2	53.7	13	40	0	3	2	1	1,100	1,100
Dondușeni	5	2	3	27.0	15.8	14	52	3.5	3	1	2	1,500	..
Drochia	4	2	2	45.5	45.5	13	59	0	1	1	0	729	729
Soroca	1	1	0	54.8	54.8	21	56	0	1	1	0	0	0
Florești	12	3	9	49.6	40.9	12	58	0.3	6	2	4	720	600
Râșcani	6	2	4	49.1	38.7	8.9	43	0.2	4	2	2	1,126	926
Glodeni	4	1	3	18.2	18.2	11	62	0	7	1	6	0	..
Fălești	2	1	1	48	40	11	62	0	1	1	0	683	683
Bălți	2	1	1	156	152	63	65	9.8	2	1	1	2,450	2,450
Sângerei	4	3	1	37.6	34.1	8.8	46	0	1	1	0	350	350
Total	**52**	**26**	**26**	**591**	**544**	**19**	**55**	**0,3**	**34**	**18**	**16**	**10,075**	**8,255**

Sources: National Bureau of Statistics [38], Association „Moldova Apa-Canal" [40]

If the number of water supply systems registers a very fast increase, by about 2.3 times, then the number of centralized sewerage systems registers an oscillating evolution against the background of a general negative trend, and the negative dynamics is found in about ½ from the districts of the region. As a result, the coverage of water supply systems with sewerage systems decreased in the analyzed period from 45% to 18%. The lack of progress in expanding centralized sewerage systems is largely due to higher costs compared to water supply systems, and most of rural people and of local public authorities do not consider this a priority [9,10,31].

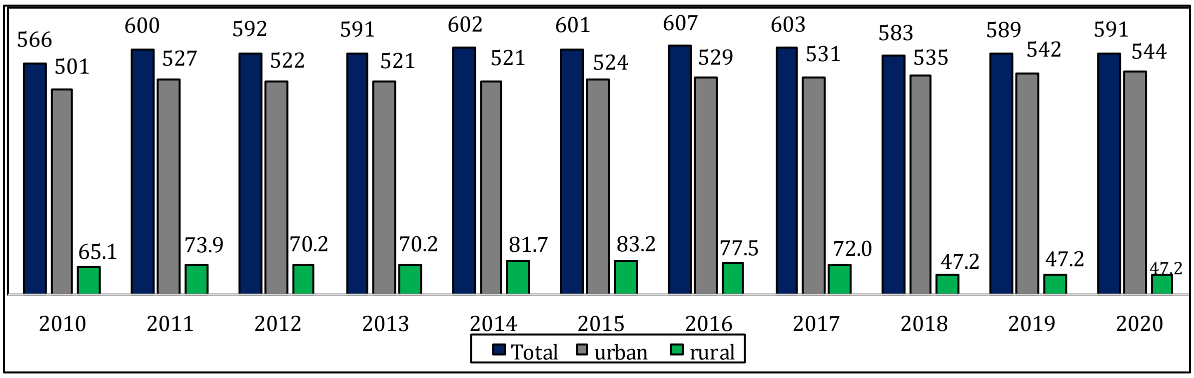

Figure 15. Dynamics of the length of public sewerage systems in North RD, km.
Sources: National Bureau of Statistics [38], Association „Moldova Apa-Canal" [40]

The length of the sewerage public systems in the North RD is about 591 km, including about 544 km (92%) in the urban areas and only 47.2 km – in the rural areas (Table 4). During the analyzed period, the length of the public sewerage systems of the study region oscillates around 600 km. In the urban area there is a slight increase (+9%) or from 501 km in 2010 year to 544 km in 2020 year. At the same time, in the rural space there is a pronounced oscillating evolution, conditioned both by the real dynamics of this indicator and by the level of evidence of the statistical and ecological authorities in the territory. Thus, from 2010 to 2015, the number of public sewerage systems in rural areas increased by 18 km, after which it decreases to 47.2 km in 2018 (Figure 15).

In 2020 year, the most extensive urban sewerage networks operate in larger cities, including Bălți (152 km), Soroca (54.8 km), Drochia (45.5 km), Fălești (40.0 km). The minimum length is found in small towns (Figure 15.), including Lipcani (1.4 km) in the district of Briceni, Otaci (3.0 km), Ocnița (4.6 km) and Frunză (10.6 km) in the district of Ocnița, Ghindești (10.9 km) from Florești district, Dondușeni (15.8 km) and Costești from Râșcani district (17.6 km) and Biruința (17.7) from Sângerei district (Table 4).

In the rural area, the most extensive sewerage networks are in the districts of Dondușeni (11.2 km) and Râșcani (10.4 km), and in the districts of Ocnița, Briceni, Fălești, Drochia and Soroca they do not exist. The most extensive rural sewerage networks operate in the villages of Duruitoarea (9.2 km) from Râșcani district and in Țaul (8.0 km) from Dondușeni district.

Despite the ambitious launch of the Water Supply and Sanitation Strategy [29], only 19% of the population in the North DR have access to centralized sewage services, including 0.3% – in rural areas and 55% – in urban areas (Table 4). The maximum access is attested in Bălți municipality (63%), as well as in Soroca districts (21%), Dondușeni (14%), which have more extensive sewerage networks. In the urban area, the maximum access is also attested in the cities of Fălești (63%), Glodeni (62%), Drochia (59%), Florești (58%) and Soroca (56%). In the districts of Soroca, Ocnița, Fălești, Glodeni, Edineț and Sângerei, have been started projects for the regionalization of water supply and sanitation services [31, 41], which will significantly increase the profitability of the respective services.

5.5.1. Use of public sewerage systems

The total volume of wastewater discharged through public sewerage networks is about 10,500,000 m^3, of which over ¾ (8,200,000 m^3) come from Bălți municipality (Table 5). During the years 2010-2020 there is a slight increase (+ 9%) of the total volume of wastewater discharged through public sewerage networks (Figure 16).

The positive dynamics is attested in 9 of the 11 districts and in the Bălți municipality. The maximum increase is observed in the districts of Dondușeni (by 1.9 times) and Ocnița (by 1.8 times), Fălești (by 1.7 times), Drochia (by 1.6 times). In Glodeni district there is a multiple reduction (by ≈5 times) of the volume of wastewater discharged, the main cause being the cessation of the activity of the sugar factory, which was also the largest generator of wastewater [33]. An insignificant reduction (by 1.2 times) is registered in Edineț district. The maximum volume of wastewater discharged into the public sewerage networks is attested in Bălți municipality (8,200,000 m^3) and the districts of Soroca (488,000 m^3) and Edineț (391,000 m^3). An average quantity was discharged in the public sanitation networks from Florești districts (248,000 m^3), Drochia (235,000 m^3), Fălești (208,000 m^3), and a minimum volume – in the smaller districts of the region (Table 5), including in Dondușeni and Râșcani (124,000 m^3) and Ocnița (70,000 m^3).

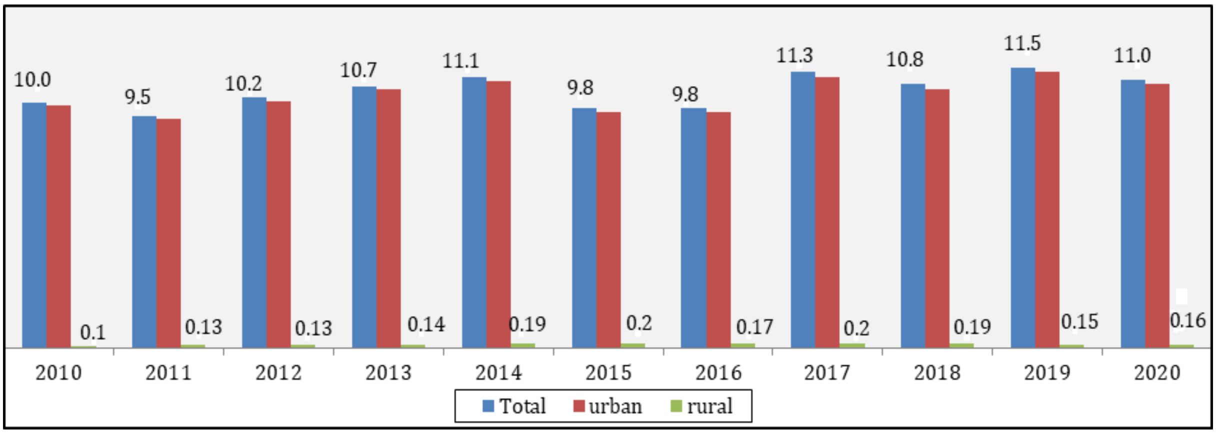

Figure 16. Dynamics of the total volume of wastewater discharged by public sewerage systems in the North RD. Source: National Bureau of Statistics [38]

On average, 10,400,000 m^3 or 98% of the total volume of wastewater discharged into the public sewerage networks in the North RD come from urban areas, including ≈100% in the districts of Briceni, Ocnița, Drochia, Soroca, Sângerei and Bălți, and ≈90% in Edineț and Dondușeni districts (Table 5).

Wastewater discharged into public sewerage networks in rural areas are present in 6 districts, the largest share being in Edineț (19%) and Dondușeni (23%) districts.

More than half (53%) of the total volume of water discharged into public sewerage systems is received from households, budget organizations and companies. In most districts of the region, the total volume of wastewater discharged and that received from subscribers is practically the same, except for Bălți municipality and Glodeni and Fălești districts. In Bălți, this difference is about 4.8 million m^3 and includes rainwater discharged into the urban sewerage network [10].

Table 5. The volume of wastewater received by public sewerage systems in the districts of RD Nord, by categories of users and living space, average of 2011-2019, in thousands m^3.

Districts	Total	Total				Households			Budget organization			Other categories		
		total	urban		rural	total		urban	total		urban	total		urban
		ths m^3	ths m^3	%	ths m^3	ths m^3	%	ths m^3	ths m^3	%	ths m^3	ths m^3	%	ths m^3
Briceni	123	120	120	100	0	83	69	83.3	27.4	23	27.4	9.2	7.7	9.2
Ocnița	71.6	62.7	62.7	100	0	54	86	53,8	6.1	10	6.1	2.8	4.5	2.8
Edineț	391	380	313	82	67.3	139	37	138	95.7	25	29.3	146	38	146
Dondușeni	125	121	97	80	20.8	79	65	78.2	35.7	29	12.2	6.4	5.3	6.4
Drochia	237	232	232	100	0	181	78	181	14.4	6.2	14.4	36.7	16	36.7
Soroca	487	487	487	100	0	342	70	342	71.1	15	71.1	73.5	15	73.5
Florești	234	230	217	95	12.4	135	59	134	19.8	8.6	18.8	74.5	32	65.0
Râșcani	123	118	117	99	1.0	72	61	71.3	23.2	20	22.4	23.5	20	23.4
Glodeni	166	132	129	98	3.1	65	49	65.0	19.6	15	16.5	47.0	36	47.0
Fălești	206	179	164	92	14.7	139	78	125	9.2	5.1	8.5	31.1	17	30.3
Bălți	8,221	3,429	3,429	42	8.1	2,280	66	2,273	327	9.5	326	822	24.0	821
Sângerei	146	135	146	108	0	95	70	94.9	27.7	20	27.7	12.7	9.4	12.7
RD Nord	**10,530**	**5,625**	**5,513**	**98**	**127**	**3,664**	**65**	**3,639**	**677**	**12**	**581**	**1,285**	**23**	**1,274**

Sources: National Bureau of Statistics [38], Association „Moldova Apa-Canal" [40]

Approximately 2/3 (3,700,000 m^3) of the total volume of wastewater discharged is received from households. Also, about 2/3 of the total volume of wastewater received from the population comes from Bălți. The maximum share (≥70%) of households is attested in Soroca, Drochia, Fălești, Ocnita districts (Table 5, Figure 17). In addition to Bălți municipality (2,300,000 m^3), the maximum volume of wastewater discharged by households is attested in the districts of Soroca (342,000 m^3) and Drochia (181,000 m^3), which have a larger population and it's a higher level of access to public sewerage networks [38]. An average amount was discharged into the public sanitation networks in the districts of Fălești, Edineț (139,000 m^3) and Florești (135,000 m^3).

From the budget organizations were discharged 677,000 m^3 (in 2019) or 12% of the total volume of wastewater discharged into the public sewerage systems in the North RD. The maximum volume of wastewater discharged by budget organizations is attested also in Bălți (327,000 m^3), as well as in the districts of Soroca (201,000 m^3), Edineț (96,000 m^3), with larger urban centers and a larger number of budget organizations located in the mentioned regional and zonal centers. The maximum share of (30%) budgetary organizations is observed in Dondușeni district, where large social and medical institutions are located, connected to the rural public network.

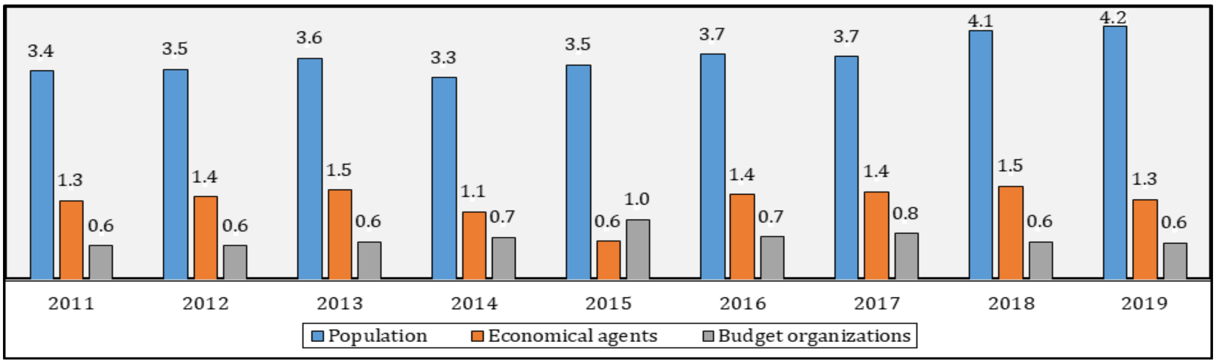

Figure 17. Dynamics of the volume of wastewater discharged in the public sewerage systems from RD Nord by categories of users, mil. m^3.

Source: National Bureau of Statistics [38]

Approximately ¼ (1,300,000 m^3) of discharged wastewater received from subscribers comes from other categories of consumers (industrial and service enterprises). In 2019, 822,000 m^3 of wastewater or

≈2/3 (64%) of the total volume of wastewater received from subscribers in RD Nord were discharged from the enterprises in Bălți in the public sewerage networks, which is what due to the concentration on the territory of Bălți of the largest industrial enterprises from this region. Also, a large volume of wastewater was discharged by the enterprises from Edineț (146,000 m^3) and Florești (75,000 m^3) districts, with a higher level of industrialization. Almost all wastewater quantity is discharged by industrial enterprises from urban areas.

5.5.2. Wastewater treatment plants

The number of treatment plants decreased in the analyzed period from 42 to 34 units (Table 4), of which only 21 with functional treatment systems. In the rural areas, the number of treatment plants has decreased significantly from 23 units in 2010 to only 16 units in 2019 [38]. Similar to the number of sewerage systems, the maximum number of treatment plants in Florești (6) and Glodeni (7) districts is explained by the fact that small sewage treatment plants were registered, serving one or several public institutions (kindergartens, schools, town halls) [10].

Over 80% of the total volume of wastewaters received from public sewerage systems is passed through treatment plants and subjected to complex treatment, including 84% in urban areas and only ≈1/3 in rural areas. The complete purification of the wastewater discharged by the public sewerage systems takes place at the treatment plants from Bălți, Edineț (Cupcini), Drochia and Ocnița towns, where measures have been taken to modernize the technological processes and equipment. Also, the normative purification is performed at the recently built treatment plants from Lipcani and in the rural localities from Florești, Glodeni and Râșcani districts [31]. In addition, in recent years has increased the degree of wastewater purification at the biological treatment plants from Drochia, Sângerei and Râșcani towns.

In the years 2018-2020 only 6% (674,000 m^3) of the total volume of wastewater discharged by public sewerage systems in the North DR were insufficiently treated, including 6% (634,000 m^3) in urban areas and 26% (41,000 m^3) in rural areas. The wastewaters discharged by the municipal enterprises from the cities of Dondușeni, Sângerei, Fălești and Florești, as well as from the rural localities from Dondușeni district, which have treatment plants [40] are insufficiently treated. In addition, treatment plants do not operate in the Soroca, Briceni and Glodeni towns, as well as in the absolute majority of rural localities [10], which generates a significant harmful effect not only on aquatic ecosystems, water resources, but also on the health of the population in those areas.

6. CONCLUSIONS

Based on the hydrographic analysis of the water flows of the Dniester and Prut rivers, for the period 1968-2020, we can observe an oscillating evolution of their flows, against the background of a general downward trend, amplified by recent climate change and the operation of hydropower complexes.

It is absolutely necessary to declare the main aqueducts as national security objectives and to apply a rigorous control over their status and operation, at the same time as expanding the capacities for distributing and consuming of water captured from quality surface sources.

The length of public aqueducts has increased by 1.7 times, including in rural areas – by 3.7 times or by 1,800 km. As a result, ≈½ of population from the North RD has a lowest access to public aqueducts, including 83% in urban areas and only 31% − in rural areas. In Briceni, Ocnița, Dondușeni and Soroca districts, is attested the lowest level of access to public aqueducts from the country.

For the (households were delivered, on average, 7,300,000 m^3 or about 80% of the total volume (excluding water delivered by SE Acva Nord). This proportion is similar in all districts and cities of the region, except the municipality of Bălți, with a higher share of industrial and transport enterprises.

The total volume of water delivered to the population increased by 1.8 times (4,100,000 m^3), including in rural areas by 4.5 times (by 2,600,000 m^3), and in urban areas, by only 35 % (1,600,000 m^3). Despite the rapid expansion of public aqueducts, per capita water consumption is low and is only 71 liters/day, including 84 liters/day in urban areas and only 53 liters/day in rural areas.

In the study region, population access to the public sewerage systems is only 19%, including 55% in the urban areas and only 0.3% – in the rural areas. There are not public sewerage systems in the villages of Ocnița, Briceni, Fălești, Drochia and Soroca districts. Slow expansion of the public sewerage systems is caused by higher costs compared to water supply systems, and most local public authorities do not consider them as a priority.

For future research, we propose to analyze the water resources, as wel as status and use of public water supply and sewerage systems in other development region and on the hydrographical basins from Republic of Moldova.

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