Urbanization effects on the river systems in the Bucharest City region (Romania)

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Abstract. This article identifies and analyzes the effects of human pressures on the river systems, landscape, flow regime, and water quality in the Bucharest region, the largest urbanized area in Romania. The analyses focused on four streams crossing the Bucharest region, namely the Dâmbovița, Colentina, Argeș, and Sabar rivers. Our approach relied especially on three types of information: (1) spatial data; (2) hydrological data sets; and (3) water quality data. We made a diachronic analysis of the available maps and ran classic statistical analysis of the data sets, as well as trend analysis. At the same time, we compared the flows in natural (reconstituted) and modified (current) regimes. The results showed that the stream system and its associated landscapes have considerably changed due to several engineering works (reservoirs, dams, channelization works, diversion canals, water intakes, etc.). Under these circumstances, the flow regime suffered changes that differed among the rivers. Thus, the multiannual discharges of the Argeș and Dâmbovița rivers did not exhibit significant changes, but only mitigated the monthly discharge variability. In the case of Sabar and Colentina, a significant increase of the annual and monthly discharges was identified, due to the water transferred from the neighboring rivers. Water quality worsened, especially on the lower courses of the Dâmbovița and Argeș rivers, degrading the states and health of the aquatic ecosystems in the study region.

Key words: aquatic ecosystems; Bucharest region; ecological state; ecosystem health; engineering works; flow regime; river system; Romania; urbanization; water quality.

Introduction

Human pressure on rivers is increasing all over the world, threatening the water security, and the aquatic ecosystem health. The problem is particularly acute in urbanized regions because the cities, due to their specific features, are a major factor influencing the water cycle, in general, and the river systems, in particular. Over the last two centuries, urbanization has caused important changes in watershed drainage system and hydrology: the rivers crossing city areas have been exploited for water supply and have been regulated, channelized, dammed, diverted, and buried (Ceola et al. 2015). As natural receptacles for urban wastewaters, the rivers undergo continuous qualitative alterations, which affect the related ecosystems’ health or their ecological integrity (Oliveira and Cortes 2006). It is therefore obvious that in urbanized areas river flow regime, water chemistry, and quality are modified, affecting the ecosystem structure, functions, and services (Su et al. 2012, Kaushal et al. 2015). The urbanization has led to an “urban stream syndrome” having as symptoms a flashier hydrograph, elevated concentrations of nutrients and contaminants, modified channel morphology, and reduced biotic richness (Walsh et al. 2005).

Many previous works have referred to the relation between rivers and urban development as well as to the effects of urbanization on landscapes and stream systems. Of these, the following are worth mentioning: Leopold (1968), Paul and Meyer (2001), Miltner et al. (2004), Meyer et al. (2005), Walsh et al. (2005), Chin (2006), Barles (2007), Kennedy et al. (2007), Grimm et al. (2008), O’Driscoll et al. (2010), McDonald et al. (2011, 2013), Pickett et al. (2011), Haidvogel et al. (2013), Hohensinner et al. (2013, 2014), Kaushal et al. (2015).

This article investigates the case of Bucharest, the capital of Romania, the country’s most representative example in terms of urban effects on river systems. It aims to provide a synthetic portrait of human interventions on the main rivers crossing the Bucharest region and to assess some of their quantitative and qualitative effects on these watercourses. The paper focuses on two main issues: (1) the major human pressures responsible
for hydrographic, hydrological, and qualitative changes in the rivers (engineering works; water abstraction for various needs; wastewater discharge) and (2) the effects of urbanization on stream network, landscape, flow regime, and water quality.

The paper supplements and updates the information generated by previous works and studies, regarding the quantitative and qualitative characteristics of water resources in the Bucharest region, on the one hand, and their management, on the other hand. The most important such studies are the following: Georgescu et al. (1966), Giurescu (1967), Jordan (1977), Pişota and Moisxiu (1977), Solacolu and Ceacir (1981), Ionescu et al. (1988), Popescu and Lăzărescu (1988), Solacolu (1988), Zaharia et al. (1997), Cocosă (1999), Zaharia and Cocosă (1999), Cocosă (2006), Soare-Bratosin (2015), Soare (2015a, b). Likewise, the Watershed management plan of Argeş—Vedea Water District (NARW 2011, MEWF and NARW 2016), the Watershed flood defense plan in Argeş—Vedea Water Branch (NARW 2015a), the County flood defense plans (NARW 2015b), and the annual environmental state reports in Bucharest City (made by the National Environmental Protection Agency) include a rich body of information concerning the watercourses in the Bucharest region and their management.

This article synthesizes and integrates information from the aforementioned studies, but at the same time delivers certain original contributions concerning the following topics: (1) diachronic analysis of cartographic documents and images, which allowed us to highlight the changes in the stream network and in the landscape associated with the rivers crossing Bucharest region; (2) comparative analysis of the average annual and monthly discharges of the main rivers in the study area, under natural (reconstituted) and modified flow regimes, analysis based on which we identified and quantified the changes induced by human pressures; (3) trend analysis of hydrological data sets variability; (4) spatial analyses regarding the ecological state of the studied rivers. The results allow a better understanding of the effects of the urbanization on watercourses, and generally of the human-coupled aquatic ecosystems functioning in the investigated area.

Study area and the main morphometric and hydrologic features of the rivers crossing the Bucharest region

Bucharest, capital of Romania since 1659, is the most important city in terms of the number of residents and its various functions (economic, political, cultural, financial, etc.). First mentioned in documentary sources in the 15th century (1459), the settlement has developed continuously, becoming the greatest urban area in the country. At present, Bucharest stretches over 238 km² (10% of the country’s area) and shelters a number of 2,140,816 people (on 1 July 2013), which accounts for about 10% of Romania’s population, with a density of 8,895 inhabitants per square kilometer (according to RSDBM 2014).

Bucharest is located in the southeastern part of the country, within the Argeş River watershed, in a region belonging to the Romanian Plain, where drainage density is high and elevations are of 60–90 m a.s.l. (Fig. 1). Its territory is crossed on a northwest–southeast direction by the Dâmboviţa and Colentina rivers, which have large floodplains and terraces where the city has found good conditions for its sprawl. However, because of this location in a floodplain area, Bucharest has high flood risk susceptibility. Consequently, in order to avoid such events, since the 18th century, the authorities have imposed a number of protection measures and have developed engineering techniques.

In the vicinity of Bucharest, there are other rivers as well: Argeş, Sabar, Ciorogârla, Ilfov, Ialomiţa, and Pasărea. Over time, all these were engineered and included in a complex management scheme, aimed at meeting the water demands of the Bucharest urban area, as well as at protecting the city against flooding. The present analysis focuses on the Dâmboviţa, Colentina, Argeş, and Sabar rivers. Their main morphometric and hydrological features are given in Tables 1 and 2.

The city’s development and the high concentration of people and socioeconomic activities have increased water consumption for various uses. In 2013, the amount of drinking water supply was 381 million m³, of which 213 million m³ for domestic use. In the same year, the wastewater volumes released in Bucharest area (Bucharest City and adjoining county Ilfov) were about 370 million m³ (RSDBM 2014).

Materials and Methods

The paper relies on several types of data: (1) information extracted from scientific literature; (2) spatial information provided by cartographic documents and images from various periods; (3) hydrological data sets concerning the average monthly and annual discharges recorded on the main rivers in the region (Argeş, Dâmboviţa, Colentina, and Sabar), which were provided by the National Administration “Romanian Waters”—the Argeş-Vedea Water Branch (NARW-AVWB); and (4) data on water quality provided by the NARW-AVWB. Table 3 shows the data/documents used and their characteristics.

In terms of methods, the paper is based particularly on the following: (1) bibliographic and cartographic research; (2) diachronic analysis of cartographic documents and satellite images; (3) statistical analyses of hydrological data sets (classical statistical parameters); (4) trend analysis in hydrological data sets variability using Mann-Kendall statistical test; and (5) spatial analysis of the ecological state of the studied rivers.

The effects of the engineering works on river flow were highlighted based on the comparative analysis
between the monthly and annual average discharges in natural flow regime \( (Q_n) \), on the one hand, and the modified regime \( (Q_m) \), on the other hand, as resulted from the data provided by the NARW-AVWB. The periods for the selected gauging stations are mentioned in Table 2 and they are depending on data availability.

The natural flow regime was reconstituted by the NARW-AVWB, based on the various water uses. To

Fig. 1. The location of Bucharest City within Romania and the Argeș River watershed (the numbers of the gauging stations correspond to those in Table 2).

Table 1. Main morphometric features of the rivers crossing the Bucharest City region.

| No | River    | \( L_t \) (km) | \( L_i \) (km)† | As (m a.s.l.) | Am (m) | S (m/km) | A (km²) |
|----|----------|----------------|----------------|--------------|--------|----------|--------|
| 1  | Argeș    | 350            | –              | 2,140        | 12     | 6        | 12,550 |
| 2  | Dâmbovița| 286            | 24.2           | 1,800        | 27     | 6        | 2,824  |
| 3  | Sabar    | 174            | –              | 349          | 37     | 2        | 1,346  |
| 4  | Colentina| 101            | 29.4           | 179          | 52     | 1        | 643    |

Note: \( L_t \), total length; \( L_i \), length in the Bucharest city area; As, headwaters elevation; Am, river mouth elevation; S, slope gradient; A, catchment area (data source: Aquaproiect 1992; †based on the measurements made on Google Satellite Layer).
quantify the difference between the natural/reconstituted ($Q_n$) and the modified/current discharges ($Q_m$), we computed the change rate ($DQ$) using the equation:

$$DQ = \frac{Q_n - Q_m}{Q_n} \times 100. \quad (1)$$

The flow variability of the two types of regimes (natural and modified) was highlighted based on the variation coefficients ($C_v$) of the annual and monthly average discharges.

Results

The main anthropogenic pressures on the rivers in the Bucharest City region

Just as in all urban areas, the rivers in the Bucharest City region are subjected to quantitative and qualitative pressures, which are mainly represented by engineering techniques, water abstractions, and wastewater discharges. The key objectives of all these are related to the aquatic ecosystem services: (1) water supply for various uses; (2) flood defense; (3) sewage collection; (4) recreation (swimming pools, wetlands, fountains), etc.

The main engineering techniques

The engineering works in the Bucharest region are mainly represented by dams, reservoirs, channelization and flow regulation works, interbasin water transfers and water intakes. These works are an integral part of the Argeș watershed management scheme, which includes the study area. The region shows a dense network of dams and reservoirs, as well as diversion and water provision canals (Fig. 2). The first significant engineering works started in the 18th century and, as the socio-economic and demographic importance of the city grew, they have developed accordingly.

Dâmboviţa River originates in the Carpathian area, at 1,800 m a.s.l., and flows into the Argeș downstream of Bucharest (Fig. 1). Its total length ($L$) is 286 km and the area of its watershed ($A$) is 2,824 km$^2$ (Table 1). The average multiannual discharge recorded at Budeşti gauging station (upstream of the confluence with the Argeș River) is about 22 m$^3$/s (Table 2). Bucharest is

Table 3. The data and documents used and their characteristics.

| No. | Type of data         | Characteristics                                                                 | Source                        |
|-----|----------------------|-------------------------------------------------------------------------------|-------------------------------|
| 1   | Cartographic documents | Military Survey maps (1/20,000; year 1900) Topographic maps (1/25,000; year 1980) | Craicușnescu et al. (2011)    |
|     |                      | Google Satellite Layer                                                        | Topographic Military Service  |
|     |                      |                                                                                | NARW-AVWB                     |
| 2   | Hydrological data sets | The average monthly and annual discharges at six gauging stations for the periods mentioned in Table 2 | NARW-AVWB                     |
| 3   | Water quality data   | Water quality classes according to the biological and physicochemical parameters measured in 12 monitoring sections on Dâmboviţa, Colentina, Argeș, and Sabar rivers in 2013 | NARW-AVWB                     |
located in the lower course of the Dâmboviţa, which crosses it on a northwest–southeast direction on about 24 km. The implementation of engineering works on this river started in 1774, when following a sequence of catastrophic flooding, Prince Alexandru Ipsilanti ordered the creation of a diversion canal upstream of Bucharest (between Lunguleţu and Brezoaele). This was meant to transfer, during high water and flood periods, discharges from Dâmboviţa River to the Sabar River, which flows to the west, through the Ciorogârla River (Georgescu et al. 1966). After the damaging floods that occurred between 1862 and 1865 in Bucharest region, the authorities built a diversion canal at Arcuda. Subsequently, the Dâmboviţa River’s training has become more and more complex, including: 13 canals for water transfer (10 of them in the Bucharest City area), which link the river to the other streams in the region, channelization works, dams, and reservoirs. At the end of the 19th century (1880–1900), Dâmboviţa’s course in the Bucharest area underwent extensive channelization and regulation works (Fig. 3). Consequently, its length within the city was reduced by about one kilometer. By the end of the 20th century, three reservoirs were completed on the Dâmboviţa River, namely: Pecineagu, with a volume (W) of 63 million m³, in the upper (mountain) sector; Văcăreşti (W = 14.5 million m³), in the middle (hilly) sector; and Lacul Morii (W = 14.7 million m³) within the Bucharest City (the volumes correspond to the normal designed stage and are according to NARW 2015a).

During the period 1985–1989, the authorities implemented the “Complex Management Scheme of the Dâmboviţa River in Bucharest,” which aimed to: regulate Dâmboviţa’s flow, protect the city against flooding,
collect and remove wastewaters and storm waters, as well as establish a number of recreation sites for the city's residents (Solacolu 1988). The engineering works mainly consisted of three elements: (1) Lacul Morii reservoir \((A = 220 \text{ ha}; W = 14.7 \text{ million m}^3)\) lying upstream the Ciurel dam (15 m high); (2) the channelization of the Dâmboviţa River within the city (downstream of the Ciurel dam), on a length of 17 km, including 11 weirs which separated slackwater pools; and (3) the wastewater drain situated under the Dâmboviţa's canal. Unlike the channelization accomplished at the end of the 19th century, the riverbed was covered with concrete and the channel was segmented by weirs (Fig. 4). Lacul Morii reservoir has multiple functions: flood peaks mitigation; Bucharest protection against overflowing; water supply of Dâmboviţa's canal downstream of the Ciurel dam (minimum 3 m\(^3\)/s) and its periodical sweep (30 m\(^3\)/s); ensuring the dilution discharge for the wastewater drain lying under the Dâmboviţa's canal (minimum 1.5 m\(^3\)/s), as well as the necessary amount of water for its periodical sweep (20 m\(^3\)/s); supplying water for the Grozăveşti thermal power station; fish breeding; irrigations and recreation (Popescu and Lăzărescu 1988, Cocoş 1999).

Dâmboviţa River is connected with the adjacent watercourses by diversion and water supply canals, which ensure interbasin transfers. Thus, there are several canals diverting water from the Argeş River to the Dâmboviţa River, with the purpose of supplementing the necessary discharges for the Bucharest's water provision (through the canals derived from Crivina, which carries the water to the Arcuda and Roşu drinking water treatment plants) and for the Lacul Morii reservoir. Together, these canals are designed to have a discharge of more than 20 m\(^3\)/s. At low and normal waters, the Dâmboviţa's flow is supplemented with water transferred from the Argeş River (namely Zăvoiul Orbului reservoir), through the CA2 canal, having a designed discharge \((Q)\) of about 12 m\(^3\)/s (NARW 2015a) (Fig. 2). In order to protect Bucharest City against flooding, during high water periods, discharges from Dâmboviţa River can be transferred into Argeş River through the Dâmboviţa—Argeş canal, which has a designed capacity of 300–500 m\(^3\)/s. Dâmboviţa River is connected with its tributary, Ilfov River, by two canals: one of them brings water from the Dâmboviţa River into Ilfov River \((Q = 8.5 \text{ m}^3/\text{s})\), while the other (Mirea Vodă canal; \(Q = 5 \text{ m}^3/\text{s}\)) has an opposite function. If necessary, it is possible to transfer water from Ialomiţa River into Dâmboviţa stream through Valea Voievozilor canal \((Q = 5 \text{ m}^3/\text{s})\) and then along Ilfov River. When Bucharest City is threatened by floods, a part of the Dâmboviţa's water can be transferred to the Argeş River by a canal (diverted from Brezoaele hydrotechnic fork), which has a maximum capacity of 300 m\(^3\)/s (the canals' discharges were taken from the NARW 2015a).

Colentina River \((L = 101 \text{ km}; A = 643 \text{ km}^2)\) crosses the northern part of Bucharest and flows into the Dâmboviţa River a few kilometers downstream of the city (Fig. 1). It originates in the plain, at an elevation of 179 m a.s.l., and has a mean gradient of 1 m/km (Table 1). The average multiannual discharges at Colacu gauging station are very low in both natural and modified flow regimes: 0.33 and 1.46 m\(^3\)/s, respectively. As a result of its different morphometric and hydrological features in comparison with the Dâmboviţa River, it was subjected to other types of engineering works. To meet the domestic water needs, the residents built a number of ponds by weirs/sluice gates emplacements. The first of such ponds (the so-called Mogoşoaia Lake) is mentioned as early as 1702. The main nuisance caused by this river was water stagnation (because of the low discharges, gentle slopes, and shallow groundwater), a phenomenon
occurring especially in summer, which was responsible for the repeated outbreaks of malaria. In 1933, statistics showed that 60–70% of the people suffering from malaria were living in the vicinity of the Colentina River (Georgescu et al. 1966). However, the authorities had begun to seek for solutions for the sanitation of the Colentina stream as early as 1929. The works started in 1933 and were completed by 1960. At present, on the Colentina River within the Bucharest area there are 15 ponds with multiple services: fishing, industrial water supply, flow regulation, and recreation (Fig. 5). All in all, these ponds have a volume of about 36 million m³ and an area of almost 14 km² (the volumes and areas correspond to the normal designed stage and are according to NARW 2015a). The ponds are fed by the water transferred to Colentina River from the adjacent streams (Fig. 2): from the Ialomiţa River through the Biliureşti canal (Q = 15 m³/s) and from the Ilfov River through the Bolovani canal (Q = 6 m³/s) (NARW 2015a).

Arges River, although it does not cross the city (passing a few kilometers to the west), plays a major role for Bucharest’s economic development. Together with Dâmboviţa River, it is the main source for the city’s water needs. It originates in the Carpathian mountains (more precisely in Făgăraș mountains) and, due to its larger drainage area, its discharge at Budeşti gauging station is almost double (47.5 m³/s) in comparison with Dâmboviţa’s (Table 2). It is worth mentioning that the Argeş River and its watershed are among the most heavily managed river basins in Romania. Between 1965 and 1997, along the Argeş River 13 multipurpose reservoirs were designed (Fig. 2). The most important in terms of volume (450 million m³) is Vidraru, which is located in the mountain area.

Over the period 1985–1989, 70% of its lower course was modified as far as the junction of the Danube (near Olteniţa City), in order to be turned into a navigable waterway meant to connect Bucharest with the Danube River. After 1990, the works were abandoned and the canal has remained unfinished (Zaharia and Cocoș 1999).

Argeş River is regulated on almost a quarter of its length. Its course is linked with adjacent streams by nine
canals for water diversion and 13 canals for water bringing (NARW 2015a) (Fig. 2).

Sabar River (L = 174 km; A = 1,346 km$^2$) passes a few kilometers west of Bucharest City. It originates in the high plain region, at 349 m a.s.l., flows into the Argeş River (at 37 m a.s.l.), and has a mean slope of 2 m/km (Table 1). Due to its proximity to the city, it was included in the comprehensive management scheme of the rivers in the Bucharest region. The Sabar River is very important for the flood control, inasmuch as its channel may serve as a diversion passage for the high waters flowing on the nearby rivers (Argeş, Dâmboviţa, and Potop; Fig. 2). Its multiannual discharge under natural flow regime is about 3 m$^3$/s, but due to water received from the neighboring streams, the recorded discharge exceeds 8 m$^3$/s (see the chapter Impact on river flow regime).

**Water withdrawals**

The rivers in the Bucharest region are the city's main water supply source, and they meet nearly all of its water needs. On the Dâmboviţa River, there are three water intakes. Two of them are found at the Văcăreşti dam; their role is to provide water for Bucharest City ($Q_i = 32$ m$^3$/s) and to supplement the discharge of the Ilfov River ($Q_i = 10.8$ m$^3$/s). The third intake ($Q_i = 20$ m$^3$/s) is situated downstream of the Ciurel dam and provides the necessary water for flushing the underground wastewater drain (NARW 2015a). On the Sabar River, there is only one water intake (at Jilava), which supplies water for irrigation ($Q_i = 10$ m$^3$/s).

Along the Argeş River, there are 13 intakes designed to provide the necessary water for various uses. The most important of them, with a designed discharge of 26.5 m$^3$/s, is located at Crivina (Fig. 2) and ensures significant amounts of water for Bucharest City. The total designed discharge of all the water intakes installed on the Argeş River is almost 190 m$^3$/s (NARW 2015a).

On the Colentina River, there are intakes only for industrial water supply located in the Pantelimon and Cernica ponds, but currently the taken volume is not significant.

To ensure the Bucharest City region's water supply, an average of 352,425 m$^3$/d is withdrawn from the Dâmboviţa River, while 353,419 m$^3$/d is collected from the Argeş River (the data are for 2013 and are according to NAPA 2014). The water extracted from the Dâmboviţa and Argeş rivers supplies three drinking treatment plants (Fig. 2). The one located at Arcuda (set up in 1888) is provided by the Dâmboviţa River and has a capacity of 650,000 m$^3$/d. The Argeş River supplies both the Roşu treatment plant (set up in 1970), with a capacity of 520,000 m$^3$/d, and the Crivina plant (which came into operation in 2006), with a capacity of 260,000 m$^3$/d (Apa Nova 2016).

**Wastewater effluents—qualitative pressures on the rivers**

In urbanized areas, water quality and, consequently, aquatic ecosystem health are considerably influenced by industrial and agricultural effluents, as well as by the wastewaters collected by the public sewerage system. In the study area, Bucharest is the main city that impacts the quality of the rivers significantly (the institution responsible for the water supply and sewerage system management in Bucharest City is S.C. Apa Nova S.A.). The storm water and the wastewaters collected by the sewage system finally reach the drain that underlies the Dâmboviţa's channelized watercourse. Subsequently, they are released in the Dâmboviţa River downstream of Bucharest City (in Glina village), where the wastewater treatment plant is located (Fig. 2). Although the construction began in 1985, it is not yet fully operational and, consequently, the spilled waters are only partly purified, significantly affecting the water quality of the Dâmboviţa.

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**Fig. 5.** Herăstrău Lake (a) and Tei Lake (b) on the Colentina River, recreation areas in Bucharest City. Source: a—https://sites.google.com/site/municipiulb/artifact; b—http://www.panoramio.com/photo/75824601.
River and its ecological state. In 2015, the Gîlna wastewater treatment plant could process mechanically above 750,000 m³/d, which represents more than 85% of the total volume of wastewater collected; at the same time, it completely purged (mechanically and biologically) 60% of the total volume. The entry into full operation mode of the wastewater treatment plant is planned for 2017, when it is expected to purify the maximum wastewater discharge of 12 m³/s designed for dry periods; at present, the plant can process mechanically up to 10 m³/s of wastewater, and completely up to 5 m³/s, while the mean designed wastewater discharge collected by the sewerage system under dry weather conditions is about 12 m³/s (Mihailovici and Soare 2015). Generally, the discharged wastewaters have high concentrations in ammonium, total nitrogen, and total phosphorous, exceeding the allowed limits in the national regulation (NARW 2011).

Colentina River receives the wastewaters discharged from the sewerage system of the Buftea City, located north of Bucharest (Fig. 1). Having passed through the mechanical and biological treatment, the effluent discharge reaches about 0.024 m³/s. The waters spilled into Colentina River usually exceed the allowed limits for suspensions content, biochemical oxygen demand, chemical oxygen demand (chromium), total nitrogen, total phosphorous, ammonium, and detergents (NARW 2011).

Upstream of the Bucharest urban area, the quality of the Argeș River is altered by the socioeconomic activities carried out in Pitești City. The main contamination source is the company responsible for water supply and sewerage (S.C. Apă Canal 2000 S.A. Pitești) (NARW 2011, Soare 2015b). Downstream of Bucharest, Argeș River collects Dâmbovița River’s polluted waters, and consequently its quality is altered significantly.

Regarding Sabar River, it is not subjected to significant qualitative pressures, inasmuch as the settlements located on its banks are rural.

At the scale of the entire study area, the largest amounts of wastewaters that are spilled into the rivers derive from the commercial companies (S.C.) responsible for urban water management: S.C. Apa Nova București S.A.—Gîlna (357.936 million m³/yr); S.C. Apa Canal 2000 S.A. Pitești (22.102 million m³/yr); S.C. Apa Nova București S.A.—Crivina Water Treatment Plant (5.194 million m³/yr), and S.C. Apa Nova București S.A.—Arcuda Water Treatment Plant (4.372 million m³/yr; the data correspond to 2009 and are according to Soare-Bratosin 2015). Over the period 2006–2011, of the total amount of wastewaters (urban, industrial, and agricultural) discharged in the Bucharest area (Bucharest City and the adjoining Ilfov County), which was nearly 400 million m³/yr, about 95% was not subjected to any treatment at all (according to Soare-Bratosin 2015 and NAPA 2012).

The effects of anthropogenic pressures
The human pressures on the rivers in the Bucharest region have caused significant changes in stream network and associated landscape, as well as in flow regime and water quality; all these changes have negative consequences on the ecosystems’ health.

Changes in stream network and landscape
The sprawl of Bucharest City and the river training have generated noticeable changes in the appearance of the stream network and river-related landscapes. These changes are highlighted by the comparative analysis of cartographic representations and images from different periods. It is obvious that, on the maps dating back to the 14th, 18th, and 19th centuries, Dâmbovița’s channel shows meanders and anabranched reaches, while its floodplain shelters wetlands, lakes, and marshes (Fig. 6a, b, c). As far as the Colentina River is concerned, the maps of 1791 and 1842 (Fig. 6b, c) show that it flowed outside the city’s perimeter and had some ponds and a floodplain with marshy areas.

To make a diachronic analysis for the period 1900–2014, we digitized the Military Survey Maps (Planurile Directoare de Tragere) of scale 1:20,000 (1900), the topographic maps of scale 1:25,000 (1980), and Google maps imagery (2014). We were thus able to identify significant changes undergone over time by the two rivers crossing Bucharest City. Nowadays, two man-made lakes (Lacul Morii and Vâcărești) and an artificial channel can be seen along Dâmbovița River, while Colentina River has turned into a chain of ponds (Fig. 7).

The present appearance of the Dâmbovița River in Bucharest City is totally different from what it looked like in the 19th century (Fig. 8). The lakes (ponds) on Colentina River provide economic (water supply for industrial and irrigation needs, fishing), aesthetical, and recreational services (Fig. 5). The canals for interbasin water transfer (Fig. 2) have induced significant changes in the stream network appearance and the watersheds hydrology in the Bucharest region.

Impacts on river flow regime
To assess urbanization effects on the river flow regime, we processed the monthly and annual average discharges recorded at the gauging stations (GSs) located on the main rivers in the Bucharest region: the Argeș River at Malu Spart GS (upstream of Bucharest) and at Budești GS (downstream of Bucharest); the Dâmbovița River at Lunguieștu GS; the Colentina River at Colacu GS; and the Sabar River at Vidra GS (the data regarding these stations are given in Table 2 and their location is shown in Figs. 1 and 2). The analyzed periods are mentioned in Table 2. To quantify the differences between the natural (reconstituted) flow regime (Qₙ) and the modified (current) flow regime (Qₘ), we computed the change rate

| River | Discharge (m³/s) |
|-------|-----------------|
| Argeș | 0.024           |
| Dâmbovița | 0.012       |
| Colentina | 0.004         |

| Month | Qₙ | Qₘ | Qₘ/Qₙ |
|-------|----|----|-------|
| Jan   | 0.01 | 0.00 | 1.00  |
| Feb   | 0.02 | 0.01 | 2.00  |
| Mar   | 0.03 | 0.02 | 1.50  |

| Station | Discharge (m³/s) |
|---------|-----------------|
| Malu Spart | 0.01 |
| Budești | 0.02 |
| Lunguieștu | 0.03 |
| Colacu | 0.04 |
| Vidra | 0.05 |
Fig. 6. Ancient maps representing the Bucharest region. (a) The Primitive plan of the capital in 1328, designed by Dimitrie Pappasoglu in 1871; (b) Austrian map elaborated by colonel Sprecht (1791); (c) Plan of Russian officer Vladimir de Blaremberg (1842)—copy made by D. Berindei in 1963 (according to Gherasim 2005, with completions).

Fig. 7. Diachronic analysis of the stream network dynamics between 1900 and 2014 in Bucharest City area, based on: Military Survey Maps (1900); topographic maps of scale 1:25,000 (1980); and Google Satellite image (2014).
(DQ), determined as we explained in chapter Materials and methods.

1. Effects on the annual and multiannual average discharges. The analysis of the variability of the annual average discharges of the Argeş River shows an alternation in periods in which the flows in natural regime were higher than those in altered regime and vice versa (Fig. 9a, b). Thereby, after 1986 both investigated gauging stations recorded a lower flow in altered regime (on an average by 40–50%), while in the previous period the altered discharges were generally higher by 30–40% in comparison with the natural ones. The differences between the two types of regimes depend on water uses and engineering work management.

For all the analyzed periods, the differences between the multiannual average discharges in natural and modified regimes are not significant. Thus, over the period 1954–2006 the multiannual natural average discharge \( \bar{Q}_{\text{nm}} \) at Malu Spart GS was 39.9 m\(^3\)/s, while the modified one \( \bar{Q}_{\text{mm}} \) was 39.4 m\(^3\)/s. Downstream of Bucharest, at Budeşti GS, for the period 1950–2006, a slight drop (by 6.5\%) of the \( \bar{Q}_{\text{mm}} \) (47.5 m\(^3\)/s) can be noticed in comparison with the \( \bar{Q}_{\text{nm}} \) (50.6 m\(^3\)/s). This fact highlights a low reduction in the mean annual flow caused by human pressures. As for the variation coefficients \( C_v \) of the annual average discharges, one can ascertain that human pressures have been responsible for the increase in the flow variability in modified regime as compared to the natural regime (from 0.29–0.31 to 0.35–0.52) (Fig. 10).

On the Dâmboviţa River, at Lunguleţu GS, the natural average discharges over the period 1988–2006 were generally lower than the values recorded before 1998 (Fig. 9c). After this period, there have been no significant differences between the two types of hydrological regimes. For most of this period, as in the case of the Argeş River, the difference between the multiannual discharges in natural and modified flow regimes is low (7%): \( \bar{Q}_{\text{nm}} = 9.9 \text{ m}^3/\text{s} \) and \( \bar{Q}_{\text{mm}} = 10.6 \text{ m}^3/\text{s} \).

Concerning the Colentina River, at Colacu GS, during the whole analyzed period (2006–2012) the natural annual average discharges were much lower than the modified ones, the differences ranging from less than 200\% to more than 1,000\% (Fig. 11a), which reflects the additional inflows. Under these circumstances, the modified multiannual average discharge is 4.4 times higher than the natural one (\( \bar{Q}_{\text{nm}} = 1.46 \text{ m}^3/\text{s} \) and \( \bar{Q}_{\text{mm}} = 0.33 \text{ m}^3/\text{s} \)).

Regarding Sabar River, at Vidra GS, the annual average discharges under natural flow regime were lower than the modified ones for the entire analyzed period (1958–2005). The differences amounted to 300–400\% (Fig. 11b). The multiannual average discharge in modified regime was 2.7 times higher than the natural one (\( \bar{Q}_{\text{nm}} = 8.2 \text{ m}^3/\text{s} \) and \( \bar{Q}_{\text{mm}} = 3.0 \text{ m}^3/\text{s} \)). As mentioned in a previous chapter, the river receives water from the neighboring streams.
2. Impacts on average monthly discharges. The analysis of the variation of the monthly average discharges under the two types of flow regimes (natural and modified) showed a similar situation for the Argeș and Dâmbovița rivers. Thus, from April to June, a period that is normally characterized by high waters, the natural discharges are higher than the modified ones. Generally, for the rest of the year the modified discharges are higher than the natural ones. The positive or negative differences between the two types of regimes may reach 20–30% (Fig. 12). This situation highlights the regulatory role of the reservoirs emplaced along the rivers.

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**Fig. 9.** Variability of the annual average discharges in natural ($Q_n$) and modified ($Q_m$) flow regimes, and of the change rate (DQ), for the Argeș (a, b) and Dâmbovița (c) rivers. $Q_{mn}$, multiannual average discharge in natural regime; $Q_{mm}$, multiannual average discharge in modified regime (in brackets, the discharge value).

**Fig. 10.** Variation coefficients ($C_v$) of the annual (a) and monthly (b) average discharges under natural (NR) and modified (MR) flow regimes of rivers crossing the Bucharest region.
For Colentina and Sabar rivers, the situation is different from Argeș and Dâmbovița rivers. Thus, the natural monthly average discharges are always lower than the modified ones. As a rule, the differences are higher during the warm season (April–October), when they can exceed 400% (up to 760%) on Colentina River and 200–300% on Sabar River (Fig. 13). This means that the two rivers receive additional amounts of water either for supplying the reservoirs/ponds (the case of Colentina River) or for flow regulation and floods control on Dâmbovița and Argeș rivers (the case of Sabar River).

The variation coefficients of the monthly average discharges during the year indicate the regulatory effect of the engineering works for all the investigated gauging stations. The reduction in these coefficients is significant (about 50%) for Argeș River (at Malu Spart GS), Dâmbovița River (at Lungulețu GS), and Colentina River, while for Sabar River, the values are

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**Fig. 11.** Variability of the annual average discharges in natural ($Q_n$) and modified ($Q_m$) flow regimes, and of the change rate ($DQ$), for the Colentina (a) and Sabar (b) rivers. $Q_{mn}$, multiannual average discharge in natural regime; $Q_{mm}$, multiannual average discharge in modified regime (in brackets, the discharge value).

**Fig. 12.** Variability of the monthly average discharges in natural ($Q_n$) and modified ($Q_m$) flow regimes, and of the change rate ($DQ$), for the Argeș (a, b) and Dâmbovița (c) rivers.
similar (0.39–0.40) for both types of flowing regimes (Fig. 10).

3. Trends in river flow variation. To identify the trends in the flow variation of the rivers crossing the Bucharest region, we applied the Mann-Kendall test on the annual and monthly discharge data sets, under natural and modified flow regimes, for Argeș River (at Malu Spart and Budești gauging stations) and Sabar River (at Vidra). The test was not applied for Dâmbovița and Colentina rivers because of the insufficient extent of the available data sets.

As Table 4 shows, under both types of regimes (natural and modified), significant downward trends (for various levels of significance) can be noticed in spring (March–May) and in the first part of summer (June–July), when the rivers usually experience high waters. In the case of Argeș River, at both analyzed gauging stations, increasing flowing trends can be noted in September and October when, as a rule, the river flow is low. Under natural regime, the trends in the discharge variation mirror the changes in the hydroclimatic parameters identified throughout the Romanian territory and at the regional level. Thus, a reduced flow in spring and summer is a direct consequence of rainfall decrease in conjunction with temperature and evaporation increase recorded in these seasons; at the same time, the snowpack supplying the rivers in springtime decreased. The upward trends in autumn flow are justified by the season’s increase in precipitation in Romania (Busuioc et al. 2010, Bîrsan et al. 2012, 2014, Bojariu et al. 2015).

Regarding the modified flow regime, the trends are the result of cumulative influences of climate variability and anthropogenic pressure. In comparison with the natural flow regime, the trends in the modified one generally have a higher level of significance; they were identified in several months vs. natural regime, including the annual discharges. This shows the effects of anthropogenic pressures on the rivers’ water resource, having as possible consequence the future decline of this resource and related water security issues.

Effects on river water quality
In Romania, river water quality is established based on the ecological state of the watercourse, according to the provisions of the European Water Framework Directive (WFD) 2000/60/EC, which have been implemented in the Romanian legislation. Consequently, the river quality is defined by taking into account biological, physicochemical, hydromorphological, and microbiological elements, each of which including specific parameters (MEWF and NARW 2016).

Table 4. Trends in the variability of monthly and annual average discharges of the Argeș and Sabar rivers, in natural and modified flow regimes.

| No | Gauging station/ River (period) | FR | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | Yr |
|----|---------------------------------|----|---|----|-----|----|---|----|-----|------|----|---|----|-----|----|
| 1  | Malu Spart/Argeș (1954–2006)    | N  |   |    |     |    |   |     |      |      |    |   |    |     |    |
|    |                                 | M  | + | ** | *** | ** | * | ** | *    | +    | *  |   |    |     |    |
| 2  | Budești/Argeș (1950–2006)      | N  | + | ** | *** | ** | * | ** | ***  | **   | *  |   |    |     |    |
| 3  | Vidra/Sabar (1958–2005)        | N  | * | +  | **  | ** | * |    |      |      |    |   |    |     |    |

Note: FR, flow regime; N, natural (reconstituted); M, modified; Yr, year; ***, trend at $\alpha = 0.001$ level of significance; **, trend at $\alpha = 0.01$ level of significance; *, trend at $\alpha = 0.05$ level of significance; +, trend at $\alpha = 0.1$ level of significance; blank cell—the significance level is greater than 0.1; in blue, downward trend; in red, upward trend.
According to the WFD, the water quality classification in Romania includes five quality classes: class I—very good quality (blue color); class II—good quality (green color); class III—moderate quality (yellow color); class IV—poor quality (orange color); and class V—bad quality (red color). The classification of the ecological state relies on the principle, “one out—all out” (i.e., the worst status of the elements used in the assessment determines the final status of the waterbody), according to the WFD provision. The same principle also applies for the quality parameters belonging to the same group (biological, physicochemical, and hydromorphological elements) (MEWF and NARW 2015, 2016).

To establish the quality of the main rivers crossing the Bucharest region (the Dâmboviţa, Colentina, Argeş, and Sabar rivers), we made use of the data provided by the NARW-AVWB for the year 2013. The analysis highlights the ecological state, based on biological and physicochemical elements (the last ones include parameters that support the biological elements). The assessment of the biological state relied on a number of parameters regarding phytoplankton, phytobenthos, and macrozoobenthos, while the physicochemical state was established based on several groups of parameters, as follows: thermal regime and acidification (TRA); oxygen regime (OR); nutrients regime (NUT); mineralization degree or salinity (SAL); natural-specific toxic pollutants (NSTP); and other relevant chemical indicators (ORCI), like phenols, detergents, and AOX. Each of the two major categories of elements (biological and physicochemical) defined a specific quality class, and, finally, the global ecological state was established. At that time, there were no data on hydromorphological parameters.

For Dâmboviţa River, the quality parameters were determined for five monitoring sections located both upstream and downstream of Bucharest City, namely at Brezoaele, Arcuda, Bălăceanca, and Budeşti. From the biological standpoint, the waters belong to quality classes III–V, especially because of the macrozoobenthos. According to the chemical indicators, the waters belong to quality classes II–V, because the values of OR, NUT, and ORCI are higher. Given these circumstances, the global ecological state of the Dâmboviţa River corresponds to the quality classes III–V. The worst condition (poor quality and bad quality) was found at the monitoring sections located downstream of Bucharest (at Bălăceanca and Budeşti), which receive the partly treated wastewaters released from Bucharest sewerage (Table 5 and Fig. 14).

Colentina River has only one station for quality measurements, located at Colacu, upstream of Bucharest (Fig. 14). From the biological point of view, the water at this monitoring station belongs to quality class IV (because of the macrozoobenthos), while from the standpoint of the physicochemical indicators it belongs to class III (because of the ORCI indicators). Therefore, the final ecological state is indicative for class IV (Table 5).

On Argeş River, four monitoring sections, located both upstream and downstream of the Bucharest City, were considered. They are located at Căteasca, Crivina (upstream of the water intake), Budeşti, and Olteniţa (Fig. 14). The analyses showed that from the biological and physicochemical points of view, upstream of Budeşti, the waters belong to quality classes II and III. Downstream of this locality, as the river receives the polluted waters of the Dâmboviţa River, water quality

| No | River/Section          | Biological state | Physicochemical state | Global ecological state |
|----|------------------------|------------------|-----------------------|-------------------------|
|    |                        | PP | PB | MZ | BS | TRA | OR | NUT | SAL | NSTP | ORCI | PCS |                      |
| 1  | Argeş/Căteasca         | II | –  | II | II | I   | I  | I   | I   | I    | I    | II  | II                     |
| 2  | Argeş/Crivina          | II | –  | II | II | I   | I  | I   | I   | I    | I    | II  | II                     |
| 3  | Argeş/Budeşti          | II | –  | III| III| I   | II | I   | I   | I    | I    | II  | II                     |
| 4  | Argeş/Clatăşti         | IV | –  | IV | IV | I   | III| IV  | I   | I    | I    | IV  | IV                     |
| 5  | Dâmboviţa/Brezoele     | II | –  | IV | IV | I   | I  | I   | I   | I    | I    | III | IV                     |
| 6  | Dâmboviţa/Aruda        | II | –  | III| III| I   | I  | I   | I   | I    | I    | II  | III                    |
| 7  | Dâmboviţa/Bălăceanca   | III| –  | V  | V  | I   | V  | V   | II  | V    | V    | V  | V                      |
| 8  | Dâmboviţa/Budeşti      | III| –  | III| III| I   | V  | V   | II  | III  | V    | V  | V                      |
| 9  | Colentina/Colacu       | II | –  | IV | IV | I   | I  | I   | I   | I    | I    | III | IV                     |
| 10 | Sabar/Tântava          | II | –  | II | II | I   | I  | I   | I   | I    | I    | II  | II                     |
| 11 | Sabar/Vârteju          | II | –  | II | II | I   | I  | I   | I   | I    | I    | II  | II                     |
| 12 | Sabar/Vidra            | II | –  | II | II | I   | I  | I   | I   | I    | I    | II  | II                     |

Note: PP, phytoplankton; PB, phytobenthos; MZ, macrozoobenthos; BS, biological state; TRA, thermal regime and acidification; OR, oxygen regime; NUT, nutrients regime; SAL, salinity/mineralization; NSTP, natural-specific toxic pollutants; ORCI, other relevant chemical indicators (phenols, detergents, and AOX); PCS, physicochemical state; I–V, quality classes (data source: NARW).
worsens, and at Clăteşti monitoring section it belongs to quality class IV, because of certain biological (phytoplankton, macrozoobenthos) and physicochemical (nutrients) indicators (Table 5).

Concerning the Sabar River, three monitoring sections were considered, located at: Tântava, Vârteju, and Vidra. As the pressures on this river are lower, water quality is better in comparison with the other streams, and it is therefore included in quality class II (Table 5 and Fig. 14).

Discussions and Conclusions

The intensive human pressures on the aquatic ecosystems in urbanized areas have led to significant quantitative, qualitative, and ecological changes, affecting their structure, functions, services, and health. The quality and, consequently, the ecological integrity/ecosystem health of any given stream are negatively correlated with the urbanization intensity in its surrounding watershed (Miltner et al. 2004, Oliveira and Cortes 2006). Given that a healthy ecosystem is crucial to provide services for society and the natural environment, designing workable strategies to achieve and maintain ecosystem health is a key future challenge for the society (Lu et al. 2015).

This paper showed the example of the Bucharest City region, which is the largest urbanized area in Romania. In the first part, the main urban pressures on the river systems (by dams, reservoirs/ponds, canals for interbasin water transfers and water intakes) are presented, while in the second part, some of the effects of these pressures on the stream network and related landscape, flow regime, and water quality are highlighted.

The engineering works in the Bucharest region are included in the complex management scheme of the Argeş River watershed, in which it is located. The study focuses on four streams, of which two cross Bucharest City (Dâmboviţa and Colentina rivers) and two pass near its western boundary (Argeş and Sabar rivers); the latter have an important role in the river scheme management in the Bucharest region. The diachronic analysis of the maps from different periods (starting with the 14th century) highlighted significant hydrographic and landscape changes, both within the city and in its hinterland.

In terms of effects on the flow regime, the two allochthonous rivers (Argeş and Dâmboviţa) did not exhibit significant alterations in the multiannual average discharges, but only the attenuation of monthly discharge variability (the average discharges in modified flow

Fig. 14. Ecological state of the main rivers crossing the Bucharest City region in 2013.
regime are lower in high water season and higher in low water periods when compared to natural regime) due to the regulatory role of the reservoirs. On the autochthonous streams (Sabar and Colentina), a significant increase in the annual and monthly average discharges was found, due to water transferred from the neighboring rivers. The trend analysis of the annual and monthly average discharges, under natural (reconstituted) and modified (current) regimes, showed significant downward trends (for various levels of significance) in spring (March–May) and in the first part of summer (June–July), while in the first part of autumn (September and October) an increasing trend was found. Under natural regime, the trends in discharge variation mirror the changes in the hydroclimatic parameters identified throughout the Romanian territory and at regional level, while in modified regime, the trends are the result of cumulative influences of climate variability and anthropogenic pressure. In comparison with the natural flow regime, the trends in the modified one generally have a higher level of significance and they were identified in several months vs. natural regime, including annual discharges.

Given that the rivers in the Bucharest region collect the wastewaters released by the urban sewage systems, which are only partially treated, the water quality of these rivers is impaired. The most heavily altered is Dâmboviţa River, which receives the wastewaters from Bucharest's sewage system, as well as the wastewaters discharged by drinking water treatment plants. Under these circumstances, downstream of Bucharest, the ecological state of the Dâmboviţa River falls in the worst quality class V (bad waters), while the Argeş River, downstream of the confluence with Dâmboviţa, falls in class IV (poor waters).

Despite the hydrographic, hydrological, and qualitative changes induced by the urban pressures in the Bucharest region, all these rivers are vital for the city’s functionality and its economic development. The engineering works proved to be effective for meeting the water demands of the urbanized area and for its flood defense. Thus, for about 40 yr (since the 1970s), Bucharest City has been protected by the flooding caused by overflowing rivers. However, the flooding caused by storm waters, which are specific to urban areas, is still a threat. Its occurrence could be diminished through the expansion and modernization of the sewerage system, but also through finding alternative techniques to the classical sewerage network that favor rainwater infiltration and storage (Zaharia 2006).

In general, Dâmboviţa and Colentina rivers are well integrated in the urban landscape and provide, among others, aesthetic and recreation services. The Dâmboviţa River, however, still requires works in order to improve the unaesthetic appearance caused by its artificial concrete channel. The river also should be better integrated and valorized in the urban development in Bucharest City, mainly through its recreational function. But the major problem to be solved is the water quality of the region’s rivers, especially in the case of the two main streams, Dâmboviţa and Argeş. It is expected that, as soon as the Gîlina wastewater treatment station starts operating at full capacity, the rivers’ quality downstream of Bucharest and the related ecosystem health will improve significantly.

In perspective, we believe that the development of urban stream restoration projects in the Bucharest City region will solve some of the specific problems concerning the urban pressures on the stream system in the area. Many studies on this topic (Lepori et al. 2005, Niezgoda and Johnson 2005, Bukaveckas 2007, Kaushal et al. 2008, Sivirichi et al. 2011, McMillan et al. 2014, Sommerhaeuser 2016) showed the benefits of stream restoration projects in urbanized areas. Stream restoration is considered to be an urban adaptation in response to watershed impairments, as it has an important role in the transition from a Sanitary City to a Sustainable City (Kaushal et al. 2015).

To maintain and improve the ecosystem health, urban strategies promoting social–ecological sustainability should be designed. They should be based on the understanding of mutual interactions within social–ecological systems and should include preemptive actions aiming to maintain the vitality of ecosystems (Lu et al. 2015). Nowadays, a challenge in urban development is the deployment of ecological urbanism, considered to be a way toward sustainable cities (Pickett and Zhou 2015). In Bucharest City, the Integrated urban development plan (IUDP) “Central zone,” approved in 2012 and adopted at the beginning of 2016 by the General Council of the Bucharest Municipality, is a major and ambitious plan for the restoration and enhancement of the urban identity. IUDP includes many projects aiming at harmonious and sustainable development of the urban area, based on its needs and potential. One of the priorities of IUDP is to regain the attractiveness of the Dâmboviţa River (BCH 2012). If so far the Dâmboviţa River’s engineering was considered mainly as a public utility infrastructure, according to the IUDP, the river should become a valuable urban element as in other capitals and European cities, such as Paris, Vienna, Budapest, Prague.

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