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The Lower Danube River

Hydro-Environmental Issues and Sustainability

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Gabriela Ioana-Toroimac
Editors

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Editors
Abdelazim Negm
Faculty of Engineering
Zagazig University
Zagazig, Egypt

Liliana Zaharia
Faculty of Geography
University of Bucharest
Bucharest, Romania

Gabriela Ioana-Toroimac
Faculty of Geography
University of Bucharest
Bucharest, Romania

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Preface

The Danube River is one of the largest European watercourses, namely the second in terms of length and basin area. It crosses the continent from west to east over a length of almost 3,000 km, from the Black Forest (Schwarzwald) Mts. (in Germany), to the Black Sea, serving as important natural corridor for socio-economic and biogeographic connections. The Danube River flows through 11 countries and many larger or smaller cities (including 4 country capitals) and villages have developed along its course. They are closely dependent on the water resources and related services provided by the river. At the same time, they are exposed to the hydrological hazards, such as the water excess (i.e., floods) and scarcity (i.e., low-waters). Furthermore, the Danube River and the adjacent floodplain host a rich and valuable biodiversity that are dependent on the quantitative and qualitative characteristics of the Danube River.

The Danube River Basin (DRB) covers about 10% of Europe and exhibits a great diversity of natural, socio-economic and political conditions. It overlaps the territories of 19 countries, being considered the most international basin in the world. Over the last century, the Danube River and its catchment were increasingly affected by human pressures (e.g., water and land uses, engineering works, water pollution etc.). They have led to more or less severe alterations of the quantitative and qualitative features of waters, and changes in morphology of the river channel and related floodplain. These pressures also impaired the functionning of the aquatic and floodplain ecosystems.

Due to the great importance of the Danube River for society and the environment, knowing its characteristics is of high scientific and practical interest for the Danubian countries. Therefore, the Danube River and its catchment have been the subject of numerous scientific publications, both at the scale of the whole river or basin, and focusing on specific issues at smaller spatial scales. An overview of the main publications on the hydrological features in the Danube River Basin is presented in Chapter "Flow Variability of the Lower Danube River: An Up-to-Date Overview" in this book. In recent years, two comprehensive books were published by Springer publishing House, dedicated to the Danube River Basin. The first one is titled "Hydrological Processes of the Danube River Basin. Perspectives from the Danubian Countries" and was edited by Mitja Brilly in 2010. It address issues related mainly to the hydrological features within the Danube River Basin. The second one, titled "The Danube River Basin", was edited by Igor Liska in 2015. It provides information on the qualitative features (chemical, biological and hydromorphological) of waters in the Danube River Basin.

This book addresses a complex topic, different from the two publications mentioned above: it focuses on the hydro-environmental issues of the Lower Danube River (LDR). The limits of this last sector of the Danube River are debatable, as shown in the Chapter "Flow Variability of the Lower Danube River: An Up-to–Date Overview". In this volume, the Lower Danube River was considered from its entrance in Romania (at Baziaș) to the Danube delta (not included in this study), over a length of about 1,000 km (see Figure 1 in Chapter "Flow Variability of the Lower Danube River: An Up-to-Date Overview"). In this sector, the Danube River is the natural border between Romania (on the one hand) and Serbia, Bulgaria, Republic of Moldova and Ukraine (on the other hand).

The information on the characteristics of the aquatic environment in the downstream sector of the Danube River is relatively sparse, so the editors and the authors decided to collaborate to produce this book focused on the Lower Danube River. It provides current findings and new knowledge about this area to the global research community and all those interested.

The book gives an overview on some of the major issues faced by the lower sector of the Danube River that was severely impacted by human pressures, especially since the second part of the last century. The two large dams on the Lower Danube River (Iron Gates I and II) and the damming of its major tributaries in this sector altered the flow regime and diminished significantly the sediment load. The narrowing forced by anthropogenic levees as well as the decrease in sediment load led to changes in riverbed and fluvial islets morphology and morphometry. These adjustments translated by alterations of aquatic habitats and biocenoses. The Lower Danube is the most polluted sector of the river, because it collects pollutants emitted by both upstream countries and those bordering the lower Danube watercourse. According to the Water Framework Directive rules, this sector was categorized as *at risk* due to pollution with nutrients and hazardous substances along its entire length on the territory of riparian countries.

In addition to the anthropogenic impacts on the Lower Danube River, there are those induced by the climate change (e.g., modifications in flow regime and in magnitude and frequency of extreme phenomena such as floods and hydrological droughts).

In this complex context, the management of the Danube River Basin (including its lower part) aims to ensure a balance between anthropogenic pressures and natural processess, in order to mitigate their negative impacts on society and environment. This remains a constant challenge and the scientific researches can provide the information support for river and basin management plans at different spatial scales.

This volume brings together contributions of authors from countries sharing the Lower Danube River and related basin. It contains 19 chapters addressing topics related to hydro-environmental issues in this geographic area, as previously outlined.

They were grouped in four parts in sequence, as follows: (1) Hydrological and Hydromorphological Processess, including four chapters; (2) Physico-Chemical Features and Quality of the Hydro-Environment, including three chapters; (3) Climate and Water Related Hazards, including six chapters and (4) Sustainable Management and Governance of the Hydro-Environment, including six chapters. In the following, we will indicate why each of the 19 chapters is presented in this book by focusing on its unique achievements.

The chapter "Flow Variability of the Lower Danube River: An Up-to-Date Overview" highlights the spatio-temporal variations of the average, maximum and minimum annual and monthly discharges of the LDR, at several gauging stations located on the Romanian bank of the river. The studied sector extends between the stations Baziaș and Ceatal Izmail (named Ceatal Chilia in Romania), over a length of about 1,000 km. The analyzed periods range from 44 years (1976–2019) to more than 170 years (1840–2012). In addition to the rigorous analysis of the Danube's flow variability at different time-scales, the chapter also includes an overview of the present state of hydrological knowledge and water management in the Danube River Basin, with a focus on its lower sector. The chapter contains 77 references and 23 figures.

The chapter "Dynamics of Islands and Danube River Channel Along Vedea-Călărași Sector (1856–2019): Hydrogeomorphological Approach" is devoted to analyze the Vedea-Călărași reach (about 135 km long) of the LDR along the border between Romania and Bulgaria. The authors are trying to answer the question "what has been the dynamics of the islands in both countries in the last century and a half, since the end of the Little Ice Age, taking into account the numerous engineering works that the Danube had suffered?". The new information based on the conducted investigations updates and complements the previous ones on the recent hydrogeomorphology of the LDR. The chapters contains 59 references and 12 figures.

The chapter "Hydro-sedimentary Modeling and Fluvial Morphological Processes Along the Lower Danube River (Giurgiu-Oltenița-Călărași Reach)" reports the morphological changes of the LDR for a better understanding of the hydromorphological behaviour of the Danube fluvial system along the Giurgiu—Călărași reach in Romania (corresponding to Ruse—Silistra reach in Bulgaria). The chapter contains analysis of the temporal and spatial morphological changes of the river channel. Water and sediment data for a period of 8 years (between 2008 and 2015) were used for the numerical model, setting up a 1D sediment transport model and calibrate it. Also, the chapter compares results with field observations and provides understanding of the complex physical processes of the hydrodynamics of sediment transport and analysis of the morphological changes (aggradation/degradation) and sediment loads in space and time, over the study period. The chapter contains 89 references and 32 figures.

The chapter "Hydro-Environmental Specifics of the Lower Danube Bulgarian Tributaries" gathers the existing knowledge with new investigated features of the Bulgarian Danube tributaries and provides useful scientific information for decision and policy makers. Three important issues have been addressed in this chapter,

(i) basic description of the Bulgarian Danube plain, considering the main geographical features (topography, climate, hydrology, etc.); (ii) legislative and management brief review, with regard to the implementation of Bulgarian and European directives (e.g. Water Framework Directive, Floods Directive), and related documents; and (iii) hydro-environmental specification concerning the Bulgarian tributaries of the LDR, their qualitative state and extreme events. The chapter contains 33 references and 16 figures.

The chapter "Water Temperature Variability in the Lower Danube River" presents a time series analysis of the water temperature recorded between 2001 and 2016. Additionally, a one-year ahead forecasting has been provided at three monitoring sections located on the Romanian side of the LDR i.e., Pristol (RO2), Chiciu (RO4) and Reni (RO5), based on data from Trans-National Monitoring Network (TNMN) of the Danube River database. The chapter contains 64 references and 7 figures.

The chapter "Variability of Nutrient Concentrations Along the Lower Danube River" provides information on the temporal and spatial variation of several nutrient concentrations (NH_4-N, NO_2-N, NO_3-N, PO_4-P and total phosphorous) between 1996 and 2017, based on data recorded at five monitoring stations located along the Lower Danube River (between km 1,071 and km 132), belonging to the Trans-National Monitoring Network (TNMN), namely: Baziaș, Pristol, Oltenița, Chiciu and Reni. The dependence of the selected nutrient contents on some hydrological and physio-chemical parameters of water (e.g. discharge, temperature, dissolved oxygen concentration) was also investigated. The chapter contains 61 references and 9 figures.

The chapter "Human Impacts on Water Resources in the Lower Danube River Basin in Serbia" presents the water resource uses including water supply, hydropower use, navigation, tourism, recreation and fishing, as well as water quality, pollution and protection of water resources. The authors assess the water quality in general and for different purposes. They used various indices and compared them to show which ones provide the added value to the water quality topic. The chapter contains 170 references and 10 figures.

The chapter "Using Köppen Climate Classification Like Diagnostic Tool to Quantify Climate Variation in Lower Danube Valley for the Period 1961–2017" provides an analysis of the Annual Climate Types (ACT) that identifies the long-term climate variability in Lower Danube Valley. The author uses temperature and precipitation monthly data for the period 1961–2017 (57 years) from 10 meteorological stations located in the Bulgarian part of Danube valley. The chapter contains 34 references and 6 figures.

The chapter "Observed Changes in the Temperature and Precipitation Regime Along the Lower Danube River" analyzes the monthly average temperatures and the monthly precipitation for five weather stations that are representative for the geographical location along the LDR: Drobeta Turnu Severin, Calafat, Zimnicea, Călărași and Galați. The authors highlight the changes occurred in the air temperature and precipitation regime along the LDR in Romania, for the period 1961–2019, based on both the meteorological data from surface measurements and MODIS satellite images. The chapter contains 37 references and 13 figures.

The chapter "A SPEI-Based Approach to Drought Hazard, Vulnerability and Risk Analysis in the Lower Danube River Region" investigates the climatic characteristics of drought for different Standardized Precipitation-Evapotranspiration Index (SPEI) timescales (a) to determine the intensity of drought hazard, (b) to estimate the degree of vulnerability to drought and (c) to determine the drought risk "hotspots" within the study region. Therefore, the authors have been analyzed the drought hazard and vulnerability to droughts in the LDR region to provide information about drought characteristics over the 1981–2019 period in the counties (Romania) and administrative districts (Bulgaria) located northward and southward along the LDR. The chapter contains 124 references and 4 figures.

The chapter "Synoptic Conditions Associated with Floods and Highest Discharges on Lower Danube River (1980–2010)" focuses on a thirty-year interval, between 1980 and 2010, when three major flood events occurred on the Lower Danube River, reaching their peak on: January 21, 1998, March 15, 2006 and June 21, 2010. Additionally, the authors clarify the large-scale atmospheric circulation conditions at continental scale. They bring new information on local and regional atmospheric circulation patterns preceding the major flood events and highest discharges pushing forward the knowledge on the regional weather patterns over the analyzed region. This aspect is very important for improving the linkages between weather and hydrological forecast. The chapter contains 35 references and 17 Figures.

The chapter "Assessment of Soil Erosion and Torrential Flood Susceptibility: Case Study—Timok River Basin, Serbia" investigates the contribution of the Timok River in total suspended sediment discharge of the Danube River, and assesses the susceptibility to soil erosion and torrential floods in the Timok River Basin, by using Erosion Potential Method (EPM) and Flash Flood Potential Index (FFPI), estimated in GIS environment. The used approaches represent a great potential for gross erosion prediction and sediment transport assessment at the river basin or regional scale. Additionally, the authors assessed the potential damage in urban areas, agricultural land and traffic communications (roads and railways) and the degree of torrential flood susceptibility in various watercourses in the Timok River Basin. The outcomes have significant interest for practical issues such as integrated water management projects, sustainable and land-use planning, spatial planning, forest ecosystems and environmental protection, sediment management, etc. The chapter contains 48 references and 6 figures.

The chapter "Hydrological Extremes Anomalies and Trends in Lower Danube Basin: Case Study—Romanian Drainage Area Between Siret and Prut Rivers" analyzes the extreme hydrological tendencies, registered between 1955 and 2018, in eastern Romania. Two data subsets were extracted, of 32 years in length, each: 1955–1986 and 1987–2018. Therefore, the analysis of extreme hydrological anomalies represents a continuation of research undergone in this field, within a region of the Lower Danube basin, in the context of ever-increasing effects of the extreme manifestations of regional climate change. Investigating extreme hydrological anomalies can aid to better understand the impact of climate change on rivers flow at regional scale. The chapter contains 41 references and 10 figures.

The chapter "A Transdisciplinary Approach Using Danube River Multi-connectivity in Wetland Management" coveres social and economic implications, considering the relationship between the natural heritage resources of the geographical subunits and the existence of the socio-economic system. The discussions include the principles and Lower Danube region examples to serve as a useful guide to ecological restoration. They serve as part of a new effort that goes beyond the current concept of natural resources conservation toward a deeper concept of restoring of "environment life"—an ecologically viable state where ecosystems are self-sustaining and improve the functioning and quality of services over time. Extensive knowledge of the risks and threats arising from the disruption of continuity and connectivity in the Danube area presents multiple opportunities to counter them. This requires an inter- and trans-disciplinary approach, as well as effective communication and cooperation between specific stakeholders in this field. The chapter contains 51 references and 13 figures.

The chapter "Anthropogenic Changes and Biodiversity Protection and Conservation Along the Lower Danube River Valley" presents an overview of the anthropogenic activities within Lower Danube River Valley, in particular Romanian part, since the end of the nineteenth century, which caused significant changes in terms of water flow, flooding regime, sediments load, morphology and biodiversity. The high degree of artificialization of the LDR coincided with the communist regime, although the damming of rivers, channelization, draining of the large floodplains has been widely practiced in many other countries. Therefore, the authors presented a review of human interventions from the last century that lead to alteration, degradation and irreversible losses of habitats along the LDR valley, restoration projects of former floodplain areas and biodiversity protection and conservation actions carried out over the area in the last decades. Additionally, the change of the political regime in all countries that overlap the LDR Basin gave the opportunity to both governments and non-governmental organizations to act for restoring of the degraded and damaged ecosystems and habitats in the LDR, as well as for the conservation of the biodiversity within. The chapter makes a review of all types of protected areas that were designed in the last three decades and nowadays they compose a very complex network. The chapter contains 129 references and 13 figures.

The chapter "Land Management Practices Favoring Environmental Conservation in the Danube Lower Valley (Romania)" demonstrates how the abandonment of the irrigation systems can generate wetlands supporting wildlife conservation within the Danube Lower Valley. For the case study in Romania, the authors established the following objectives: (i) identify the spatial distribution of protected areas (SCI and SPA) within the Danube Lower Valley, created in landscapes with abandoned irrigation systems, based on GIS techniques; (ii) model the dynamic of artificial and natural land cover classes within the Danube Lower Valley through landscape ecology metrics and (iii) explore the implications of abandoned irrigation systems on biodiversity, based on cross-referencing the available scientific biogeographical literature. The chapter contains 39 references and 7 figures.

The chapter "The Danube River: Between Conservation and Human Pressures in the Iron Gates Natural Park" analyzes the integration of competing social and economic objectives with the conservation process of the Iron Gates Natural Park (IGNP), with a special focus to the Danube River. The authors proposed for this a three-staged analysis: (i) assessing the current social and economic situation of the communities living within IGNP; (ii) classifying the conservation objectives and measures presented in the Management Plan of the IGNP, and (iii) identifying public perceptions on the conservation status of the area. The authors focused on describing in this chapter an integrated perspective, including both socio-economic and conservation realities specific to the IGNP, as prior studies have analyzed just one of these perspectives. The chapter contains 58 references and 10 figures.

The chapter "Citizen Science for the Danube River—Knowledge Transfer, Challenges and Perspectives" examines the activities with citizen involvement in the region and the best practices that can be implemented for environmental monitoring. The educational, social and economic barriers in citizen science projects success and impact are discussed. This chapter also explores the dynamics between the involved parties (scientists, citizens, water managers and policy-makers). The potential tools that can be used to optimize public participation programs were identified. The chapters contains 93 references and 4 figures.

The chapter "Stakeholders' Interests and Participation in the Sustainable Use of the Lakes Along the Danube Floodplain. A Romanian Sector as Case Study" proposes a comprehensive framework to establish and implement stakeholder's interests and participation in sustainable use of the Danube Floodplain lakes (Romania), from stakeholder identification to their level of involvement and provides new and original information on this topic, derived from own research. In this sense, assessing stakeholders' involvement can contribute to the sustainable use of lakes by paying attention to the increasing involvement of public institutions with decision making power in the sustainable use of floodplain lakes. The chapter contains 72 references and 10 figures.

The editors want to express their special thanks to all who contributed to make this high-quality volume a real source of knowledge by presenting the latest findings in the Hydro-Environmnetal aspects of the Lower Danube River. We would like to thank all the authors for their invaluable contributions. Without their patience and effort in writing and revising the different versions to satisfy the high-quality standards of Springer, it would not have been possible to produce this book and make it a reality. Much appreciation and great thanks are also owed to the reviewers of the chapters and the editors of the Earth and Environmental Sciences series at Springer, for the constructive comments, advice and the critical reviews. Acknowledgments are extended to include all members of the Springer team who have worked long and hard to produce this volume.

The volume editors would be happy to receive any comments to improve future editions. Comments, feedback, suggestions for improvement or new chapters for next editions are most welcome and should be sent directly to the volume editors.

Zagazig, Egypt Abdelazim Negm
Bucharest, Romania Liliana Zaharia
Bucharest, Romania Gabriela Ioana-Toroimac
January 2022

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Hydrological and Hydromorphological Processess

Flow Variability of the Lower Danube River: An Up-to-Date Overview

Liliana Zaharia, Gabriela Ioana-Toroimac, Gabriela-Adina Moroșanu, Elena Țuchiu, Gabriela Osaci-Costache, and Abdelazim Negm

Abstract This chapter provides an up-to-date overview of the flow variability of the Lower Danube River, on a length of about 1,000 km, from the entrance in Romania (at Baziaș) to the beginning of the delta (at Ceatal Izmail or Ceatal Chilia, in Romania). It highlights the spatio-temporal variation of the average, maximum and minimum annual and monthly discharges of the Danube River, at several gauging stations located on the Romanian bank of the river. The analyzed periods range from 44 years (1976–2019) to more than 170 years (1840–2012). Between Baziaș and Ceatal Izmail, the multiannual discharge of the Danube River increased by almost 1,000 m^3/s (from 5,551 to 6,516 m^3/s, during the period 1840–2012), as a result of tributaries' contribution from the riparian countries (Romania, Serbia, Bulgaria, Republic of Moldova, Ukraine). The flow regime of the Lower Danube River shows the highest discharges in spring and early summer (April–June, with the peak in April) and the lowest discharges in late summer–autumn (August-November, with minimum

L. Zaharia (✉) · G. Ioana-Toroimac · G. Osaci-Costache
Faculty of Geography, University of Bucharest, Nicolae Bălcescu Blvd. 1, 010041 Bucharest, Romania
e-mail: liliana.zaharia@geo.unibuc.ro

G. Ioana-Toroimac
e-mail: gabriela.toroimac@geo.unibuc.ro

G. Osaci-Costache
e-mail: gabriela.osacicostache@geo.unibuc.ro

G.-A. Moroșanu
Institute of Geography of the Romanian Academy, Str. Dimitrie Racoviță 12, 023993 Bucharest, Romania
e-mail: gabriela.morosanu@unibuc.ro

E. Țuchiu
National Administration "Romanian Waters", Str. Ion Câmpineanu 11, 030167 Bucharest, Romania
e-mail: elena.tuchiu@rowater.ro

A. Negm
Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt
e-mail: amnegm@zu.edu.eg; amnegm85@yahoo.com

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in September). During the period 1931–2019, the highest maximum discharges occurred during the historical flood in 2006. They reached 15,800 m^3/s at Baziaș and 15,900 m^3/s at Ceatal Izmail, but at some intermediate gauging sections the discharges exceeded 16,000 (e.g. 16,300 m^3/s, at Giurgiu, 16,200 m^3/s, at Oltenița). During the same period, the minimum discharges decreased up to 1,040 m^3/s at Baziaș (in 1949) and 1,790 m^3/s at Ceatal Izmail (in 1947). The two large dams and reservoirs built on the Lower Danube River within the hydroelectric and navigation systems Iron Gates I and II, did not significantly impair the water flow of the Danube River, but mostly the sediment flux.

Keywords Discharge · Spatio-temporal variability · Flood · Danube River · Romania

List of Acronyms and Symbols

DRB	Danube River Basin
DRBMP	Danube River Basin Management Plan
DRPC	Danube River Protection Convention
EC	European Commission
EEC	European Economic Community
EU	European Union
FRMD	Flood Risk Management Directive
FRMP	Flood Risk Management Plan
HENS	Hydroelectric and Navigation System
h.s.	Hydrometric station
ICDPR	International Commission for the Protection of the Danube River
IHP/UNESCO	UNESCO International Hydrological Program
LDR	Lower Danube River
NARW	National Administration "Romanian Waters"
NIHWM	National Institute of Hydrology and Water Management
WFD	Water Framework Directive

1 Introduction

Since ancient times, the large rivers have been the main water source for the various needs of the riparian settlements, supporting their socio-economic development. Furthermore, they fostered the connections between human communities along the rivers and between geographical regions. This is also the case of the Danube River, a major European fluvial and polarization axis [1], which crosses the continent from west to east over a length of 2,857 km [2], from the Black Forest Mts. (Schwarzwald), in Germany, to the Black Sea, in Romania and Ukraine. The Danube River Basin (DRB) extends over an area of 801,463 km^2 [2], i.e. about 10% of Europe's territory (in [3], the Danube's length is 2,826 km and the catchment area is 817,000 km^2). The Danube catchment overlaps the territories of 19 countries and hosts approx. 80.5 million people, being considered the most international basin in the world [2]. The largest share of the total area and the number of inhabitants belongs to Romania (about 30% and 22% respectively). Due to its large size, the basin exhibits a wide variety of natural, socio-economic and political conditions [4]. It has a rich ecological variety and holds the highest freshwater biodiversity in Europe [2, 5]. The Danube River serves as important West–East corridor for species migration, connecting different biogeographic zones [6].

Three main sectors of the watercourse (and of the basin) can be distinguished along the Danube River: the Upper, the Middle and the Lower Danube (Fig. 1). They differ substantially in their features and are separated by two gorges on the Danube River: the Davin Gate (between the Upper and Middle sector) and the Iron Gates (between the Middle and Lower sector). The Upper Danube has a length of about 620 km from the source to its confluence with the Morava River, at Bratislava [7]. The related basin has a predominantly mountainous relief, reaching 4,052 m a.s.l. in the south, in the Alps [7]. The Middle Danube drains the large depression of the Pannonian plain over a length of about 930 km, but the related basin overlaps, at its extremities, mountainous areas (i.e. the Alps, the Dinarides, the Carpathians) [3, 7]. Along the middle sector, Danube River receives three major tributaries (Drava, Tisza, and Sava rivers) that substantially increase its flow. The Lower Danube extends from

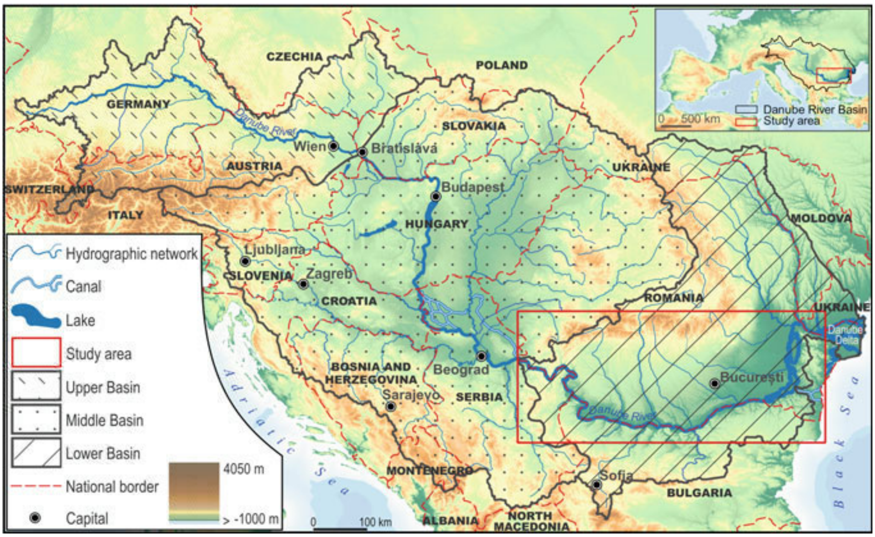

Fig. 1 The Danube River Basin and the location of the study area (the red frame marks the limits of the Lower Danube River sector, as considered in this chapter and the book). The digital terrain model was extracted from [9]

the Iron Gates to the Danube Delta and the Black Sea. Its exact limits are debatable, as discussed in Sect. 3.1. According to [7], the length of the Lower Danube is about 863 km, without the delta, that is considered a separate river section. The Lower Danube crosses the Romanian-Bulgarian lowlands, bordered by the Carpathians Mts. (in the north) and the Balkan (Stara Planina) Mts. (in the south). The Danube Delta cover a total area of about 6,750 km^2 in Romania and Ukraine [8].

The Danube River crosses 11 countries and 4 capitals (Wien, Bratislava, Budapest and Belgrade) serving as a major waterway that connects Central Europe and Southeast Europe. Along the Danube River, several large cities and hundreds of small towns and villages are located. Their existence and development are closely dependent on the Danube River, which is used for various purposes (domestic and industrial water, irrigation, hydropower generation and navigation).

The DRB is one of the most human impacted large river catchments in the world [10]. The anthropogenic pressures altered the hydro-sedimentary flows and channel morphodynamics, as well as the water quality and ecological status [7]. In addition to the human pressures, the hydrological features of the Danube River are impacted by climate change-related processes [7, 11]. In this complex context, the investigation of the hydrological features of the Danube River is of high interest both scientifically and, especially, practically, to provide up-to-date information useful for adequate water and basin management.

Because of their great importance for society and the environment, the Danube River and its catchment were intensively studied, both at the scale of the whole river or basin, and focusing on specific issues and sectors/areas. General information on the wide-basin environmental features is found in several monographic works such as [12–15].

In this chapter, we focused on the hydrological features of the Lower Danube River (LDR), less studied from a hydrological point of view than the upstream sectors. The chapter provides an up-to-date overview of the Danube's long-term flow variability over periods ranging from 44 years (1976–2019) to 173 years (1840–2012). It highlights the temporal and spatial variation of the average, maximum and minimum discharges from the entrance of the Danube River in Romania (at Baziaș) to the beginning of its delta (over a length of about 1,000 km), based on data from several gauging stations located on the Romanian side of the river.

2 Overview of the Present State of Hydrological Knowledge and Water Management in the Danube River Basin

It can be considered that the study of Danube River's hydrology, based on systematic measurements, began in the first part of the nineteenth century. The international nature of the river has required the scientific transboundary cooperation, in the field of hydrology, between the countries sharing the Danube catchment. This cooperation began in 1961 and continues to this day. Since 1975, it has been held in the framework of the International Hydrological Program (IHP) within UNESCO's Division of Water Sciences and it has included two major types of activities: organizing scientific conferences and developing thematic projects and monographs on the DRB [16, 17].

The scientific outputs of the cooperation between the Danube basin countries were materialized in several works (reports and books) on the hydrological features of the Danube River and its catchment. The most relevant are the monographic works (as quoted in [17]): "Die Donau und Ihr Einzugsgebiet – Eine hydrologische Monographic" (1986, in German; München), "Donau i ego basseyn – Gidrologicheskaya Monografiya" (1989, in Russian; Leningrad), and "Danube: hydrology of the river" (1988, in English, Russian, German and French; Bratislava).

The Hydrological Monograph of the Danube River and its catchment, published in German in 1986 [18], represents a major integrated approach on the Danube River and its tributaries, issued from the cooperation between the Danube countries [17]. It includes three chapters [3, 16]; (1) physical, geographical and water management characteristics of the river basin; (2) characteristics of the flow regime of the Danube River and its major tributaries (1931–1970) and (3) hydrological balance for the period 1931–1970.

In the following years, the Danube monograph was completed with other studies and publications (follow-up volumes), resulting from the cooperation between the Danube countries within the framework of the UNESCO International Hydrological Program (IHP/UNESCO). These scientific works provide additional and updated information on hydrological features in the Danube River basin (e.g. flow and sediment regime, thermal and ice conditions, water balance, flood regime etc.).

A recent comprehensive publication on the hydrological characteristics of the Danube basin, including results of the collaboration between Danube countries within the framework of IHP/UNESCO, is represented by the book "Hydrological Processes of the Danube River Basin – Perspectives from the Danubian Countries", edited by Mitja Brilly and published by Springer in 2010 [19]. In 2015, Springer published the book "The Danube River Basin" (edited by Liska), focused on the chemical, biological and hydromorphological features/characteristic of the Danube River [20].

The most recent follow-up volume (IX) of the Hydrological Monograph of the Danube Basin was published in 2019 and is dedicated to the flood regime of rivers [21]. Additional details on the hydrological cooperation within the DRB and the scientific products can be found in [16, 17].

The overall legal framework for cooperation and transboundary water management in the DRB is the Danube River Protection Convention (DRPC), signed on June 29, 1994 in Sofia (Bulgaria), which came into force in 1998. Its main objective is to ensure a sustainable and equitable water management within the DRB [22]. Responsible for implementing the DRPC is the International Commission for the Protection of the Danube River (ICPDR), a transnational body established in 1998. It serves as a coordinating platform addressing multiple issues within the Danube River Basin/District [23]. ICPDR also coordinates the implementation within the DRB of all transboundary aspects of the EU Water Framework Directive (WFD) (2000/60/EC) and of the EU Flood Risk Management Directive (FRMD) (2007/60/EC). To meet the objectives set out by the WFD, the ICPDR elaborated the "Danube River Basin Management Plan"—DRBMP (and its updates) for three cycles: 1st DRBMP (2009–2015), the 2nd DRBMP (2015–2021) and the 3rd DRBMP (2021–2027). These plans include wealth of information on the DRB features, focusing on: the significant pressures impacting the water bodies; the assessment of the ecological status/potential and chemical status of the surface waterbodies; the quantitative and qualitative status of groundwaters; water management issues and measures required to be undertaken by the Danube countries to achieve the WFD objectives [2, 24]. The plans are accompanied by numerous maps and annexes containing a large amount of information on the Danube River and its catchment. In order to mitigate the flood risk in the DRB and to meet the requirements of the EU FRMD, in 2015, ICPDR developed the "Flood Risk Management Plan" (FRMP) for the Danube River Basin district. It highlights the main objectives and issues related to flood risk management at the basin-wide spatial scale. Following a 6-year cycle, FRMP has been updated in 2021. More detailed information and measures related to flood protection, prevention and mitigation are provided by the flood risk management plans developed at national level [25]. A valuable publication on flood risk along the Danube River is the "Danube Atlas - Flood Hazard and Risk Maps" (2012), the key product of the Danube Flood Risk Project. This Atlas is part of the ICPDR Action Program for Sustainable Flood Protection in the DRB and a contribution to the implementation of the EU Danube Strategy [26]. The maps in the atlas (printed in a scale of 1:100,000) show the areas exposed to flood hazard for three flood scenarios (with 30, 100 and 100 years return period) and the potential damage/flood risk [27].

Besides the major reference works on the entire Danube River and its basin mentioned above, the scientific literature abounds in publications providing vast amounts of information on hydrological topics related to the Danube River and its catchment, at various (smaller or larger) spatial scales. However, hydrological information regarding the Lower Danube River is relatively scarce and generally outdated. Therefore, in this chapter, we focus the investigation on this downstream sector of the Danube River, an area with a very high economic and ecological importance, providing an updated overview on the Danube's flow variability.

3 Study Area

In the first part, this section provides information on the general features of the study area. Further, an overview of the relevant previous hydrological studies on the LDR and data on the analyzed gauging stations are presented.

3.1 General Features

According to [8] the Lower Danube River and its related catchment extend downstream of the Iron Gates gorge, to the Danube's mouth in the Black Sea. Before reaching the sea, the Danube develops a large delta, between three main branches (Figs. 1 and 2). However, the limits of the Lower Danube sector are debatable. Thereby, in some papers, most of them based on data derived from ICPDR (e.g. [3, 7, 15, 28]), the western limit of the Lower Danube sector is the Iron Gates I dam, while in other papers, this limit is considered at the entry of the Danube River in Romania, at Baziaș (e.g. [1, 29, 30]). The Danube Delta is not always included in the lower sector of the Danube River, thus in some publications it is seen as a distinct region, due to its special environmental and hydrological features (e.g. [7, 15, 28, 29, 31]).

The study area considered in this chapter overlaps the Lower Danube River sector, with a length of almost 1,000 km, between the hydrometric stations of Baziaș (located at 1072 km away from the Danube's mouth) and Ceatal Izmail (or Ceatal Chilia, in Romania), located at 79,6 km from the Danube's mouth, just before the Danube Delta entrance (Fig. 2). Along the studied sector, the Danube River forms the Romania's natural border with the neighbouring countries: Serbia (in the south–west), Bulgaria (in the south), Ukraine and the Republic of Moldova (in the south–east) (Figs. 1 and 2).

Except for the western part, where the Danube River crosses the Carpathians through a spectacular gorge, the LDR drains lowland areas and is bordered by a floodplain with variable width (wider on the left side, in Romania, where it reaches up to 30 km). Starting with the XXth century, the Danube floodplain in Romania was subject of engineering works (embankment, drainage etc.), extensive after 1960.

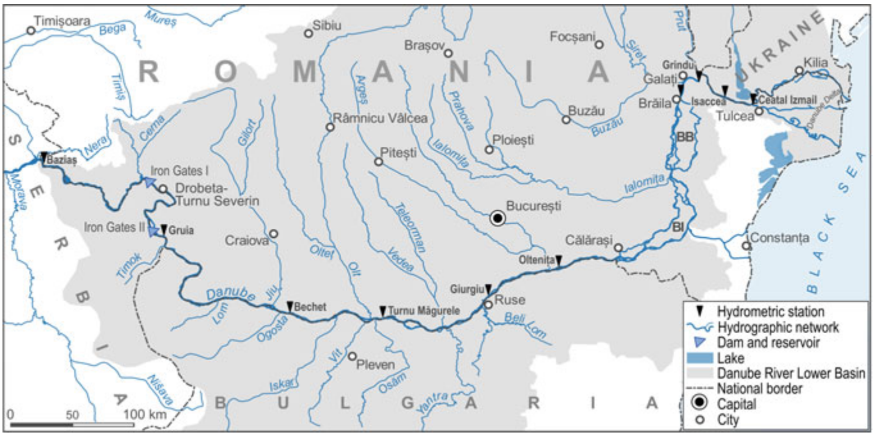

Fig. 2 The study area and the location of the analyzed hydrometric stations (BI—*Balta Ialomiței*; BB—*Balta Brăilei*)

They aimed at agricultural and industrial development, supporting fluvial transport and preventing flood events. As a result of embankment and drainage works, important areas within the Danube floodplain were transformed into agricultural land, poplar plantations and fish ponds [15]. Consequently, about 80% of the Danube's natural/original floodplains [32], including many wetlands and lakes together with the related ecosystems, have disappeared. The transformation of the Lower Danube floodplain was considered the most devastating anthropogenic alteration of a fluvial wetland in post-war Europe [33]. In recent decades, in the new context of sustainable development and of the requirements set by European (EU) legislation/directives (mainly *EU Water Framework Directive*—2000/60/EC*, EU Flood Risk Management Directive*—2007/60/EC, and *Habitats Directive*—92/43/EEC), there is a new, ecological perspective on the management of the Lower Danube floodplain, aiming at the restoration, as far as possible, of its state, by removing of engineering structures and reconnecting the former wetlands with the river channel [33]. To this end, several programs and projects were initiated, promoting wetland protection and restoration activities, such as: the *Lower Danube Green Corridor* (based on the joint declaration of the governments of Bulgaria, the Republic of Moldova, Romania, and Ukraine, signed in 2000) [34], the *Ecological and economic resizing program in the Romanian sector of the Danube floodplain* (approved by the Romanian Government in 2006) [35] and the *Danube Floodplain* project [36].

The area studied in this chapter includes four sectors along the LDR, with particular environmental and hydrological features. They are briefly presented below, from downstream to upstream.

(1) From Baziaș to Drobeta-Turnu Severin, the Danube River forms a gorge with a length of 144 km, known as the Iron Gates (*Porțile de Fier*, in Romanian, or *Đerdap* in Serbian), crossing the Carpathians, with steep slopes and spectacular landscapes as in the *Cazane* (in Romanian) area. The tributaries are short, with relatively small catchments and low water flow. The most important is Cerna River (in Romania), with an average multiannual discharge (Qav) of about 24 m^3/s [37]. To improve the navigation conditions and exploit the important hydropower potential of the river in this mountainous area, between 1964 and 1971, at the eastern extremity of the gorge (at km 943), a dam was built with the largest reservoir and hydro-power plant along the entire Danube River. Its initial capacity of 2100 MW was later increased to 2532 MW [38, 39]. The complex arrangement, known (in Romania) as the *Iron Gate I Hydroelectric and Navigation System* (HENS) was constructed between 1964 and 1971 and became fully operational in 1972 [38, 40, 41]. Romania and Serbia jointly manage the system.

(2) The sector between Drobeta-Turnu Severin and Călărași cities (of about 570 km in length) is caracterized by an asymmetrical terraced valley, more developed on the Romanian side. The Danube River flows from West to East, between the Romanian plain (in the north) and the pre-Balkan plateau (in the south, in Bulgaria). A specific feature of this sector of the Danube River is the presence of numerous islets and fords, favoured by the low slope of the riverbed and of the

water line [42]. Another particular feature is the presence of a well-developed floodplain on the left (Romanian) side, with variable width (2–15 km) [29]. Before the extensive engineering works carried out in the second half of the twentieth century (embankments and draining), the floodplain included numerous lakes [1, 33].

Downstream of the Iron Gates I dam, a second Hydroelectric and Navigation System, named (in Romania) Iron Gates II, was built on the Danube River. It is also jointly managed by Romania and Serbia. This system includes two dams located on the branches of the river that surround the *Ostrovul Mare* island: a dam is on the main branch of the Danube River (at km 862.8) and the second one, on the secondary branch (named Gogoșu), at km 875 [39]. The construction works started in 1977 and the system became fully operational in 1986 [38, 39]. The total capacity of the power stations increased from 486 MW (the initial capacity), to about 600 MW (after upgrading the turbines) [38, 39, 41].

Between Drobeta-Turnu Severin and Călărași, the Danube River receives several tributaries, among which the most important are: Jiu, Olt and Argeș rivers (in Romania), Timok (at the Bulgarian-Serbian border) and Iskar and Yantra rivers (in Bulgaria), with multiannual discharges ranging from 31 m^3/s (Timok River) to 174 m^3/s (Olt River) (Table 1).

(3) The sector between Călărași and Brăila cities (about 200 km in length) has as particular feature the branching of the Danube River into several arms and

Table 1 Main tributaries of the Lower Danube River and their specific features

River	Side	Length (km)	Catchment area (km^2)	Average discharge (m^3/s)
Cerna	Left	87[a]	1,360[a]	23.9[a]
Timok	Right	180	4,630	31
Lom	Right			
Jiu	Left	339	10,080	86
Ogosta	Right	147[b]	3,157[b]	18[b]
Iskar	Right	368	8,684	54
Vit	Left	189[c]	3,252[c]	14.6[c]
Olt	Right	615	24,050	174
Osam	Left	314[c]	2824[c]	13.1[c]
Vedea	Right	224[d]	5,430[d]	13.8[e]
Yantra	Left	285	7,879	47
Argeș	Right	350	12,550	71
Ialomița	Right	417	10,350	45
Siret	Right	559	47,610	240
Prut	Right	950	27,540	110

Data Sources [8], excepting superscripts a–d, taken from other sources, as follows:
[a][37]; [b][43]; [c][44]; [d][45]; [e][46]

the presence of two large islands (named *bălți*, in Romanian), a reason why this stretch is still called the "*bălți*" sector. The two large islands are: *Balta Ialomiței* (to the south, with a length of about 100 km, maximum width of 15 km and area of 880 km^2) and *Balta Brăilei* (to the north, with a length of 60 km, maximum width of 20 km and area of 960 km^2 [29] (Fig. 2). These islands were mostly embanked and drained to use the land for agriculture.

Unlike the previous sectors where the Danube River has a general flow direction from west to east forming the border between Romania (on the left side) and Serbia and Bulgaria (on the right side), in this sector the river flows from south to north, entirely within the Romanian territory. Between Călărași and Brăila cities, the Danube River has very few tributaries, the most important being Ialomița River, with Qav = 45 m^3/s [8] (Table 1).

(4) The last sector extends from Brăila city to the division of the Danube River into two arms at Ceatal Izmail (or Ceatal Chilia, in Romania) within Pătlageanca village, right before the entrance in the Danube Delta. In this sector, the river has a single channel. Between the cities of Brăila and Galați the river flows to the north, and downstream Galați, the flow direction changes by 90°, the river heading towards east. At the end of the nineteenth century, the river channel in this sector was subjected of important engineering works to facilitate the navigation of heavy ships (maritime) between the Black Sea and the harbor of Brăila. Within this sector (almost 90 km long) also called Maritime Danube [1, 47], the river collects from the left side the waters of two of its largest tributaries in the lower course, Siret (Qav = 240 m^3/s) and Prut (Qav = 110 m^3/s) rivers [8] (Tabel 1).

Along the LDR, the climate is of temperate-continental type, but with different influences induced by the regional atmospheric circulation: Mediterranean and oceanic influences in the west (determined by Atlantic and Mediterranean cyclones), while in the eastern part there are Pontic (induced by the vicinity of the Black Sea and the cyclones formed in its area) and arid influences (generated by the Euro-Asian anticyclones). The large aquatic surfaces of the Danube River and related floodplain determine local peculiarities and the existence along the watercourse, of a specific "Danubian" topoclimate [29]. The morphology and orientation of the valley influence the direction and speed of the air mass circulation. More detailed information on the climate along the LDR are provided by the Chapters "Using Köppen Climate Classification Like Diagnostic Tool to Quantify Climate Variation in Lower Danube Valley for the Period 1961–2017" and "Observed Changes in the Temperature and Precipitation Regime Along the Lower Danube River" of this book.

The favorable living conditions along the LDR and the natural resources offered by the river and its floodplain favoured the intense population of the adjacent area and the development of numerous settlements on both banks of the Danube River. Some of these are regional centers and county residences with over 50,000 inhabitants (e.g. Drobeta-Turnu Severin, Giurgiu, Călărași (in Romania) and even over 100,000 inhabitants (e.g. Brăila and Galați, in Romania, and Ruse in Bulgaria). Danube River is a key natural resource for the existence and development of not only riverside settlements, but also of a larger area, due to the multipurpose uses of the river: water supply (for agriculture/irrigation, industry, domestic consumption), fishing, hydropower generation, fluvial navigation, tourism and recreation. The use of the watercourse for fluvial transport favoured the connexions between the countries from the different sectors of the Danube. All these uses are closely dependent on variations in river's level and flow. In extreme cases (e.g. floods and low waters), the flow fluctuations can cause serious damage to society. Furthermore, the LDR and the adjacent floodplain host a rich and valuable biodiversity, equally dependent on the fluctuation of Danube's water [15].

3.2 Overview of the Hydrological Knowledge on the Lower Danube River

Because of the crucial economic and environmental importance of the LDR, the riparian countries were concerned with conducting hydrological studies providing information on the flow variability, essential for water and related risks management. In Romania, comprehensive information on the hydrological features of the LDR are provided by two monographic publications (both in Romanian): *Dunărea între Baziaş şi Ceatal Izmail. Monografie hidrologică* (*The Danube between Baziaş and Ceatal Izmail. Hydrological monograph*) [48] and *Geografia Văii Dunării Românești* (*Geography of the Romanian Danube Valley*) [49]. Likewise, more or less synthetic information on the hydrological characteristics (including flow variability) of the LDR are included in dedicated chapters in several books such as [29, 50–53].

In addition to the volumes (such as those mentioned above) including hydrological information on the LDR, there are numerous papers published in scientific journals and conference proceedings, which address topics related to the flow variability in the Lower Danube River, of which we mention: [1, 28, 54–68]. An analysis of the variation of the average, maximum and minimum flows at several stations along the LDR, in the period 1931–2016 is performed in [69].

Information on the hydrological features of the Lower Danube River is also found in the publications carried out at the wide-basin scale, as already mentioned in the previous Sect. 2.

This chapter completes the existent information on the Danube's flow in its lower sector, providing an updated overview on the long-term variability of the average, maximum and minimum discharges at several gauging stations in this sector.

3.3 Data on the Analyzed Hydrometric Stations

The analysis carried out in this chapter is mainly based on processing flow data series recorded at hydrometric/gauging stations (h.s.) located along the LDR, on the left (Romanian) side, belonging to the Romanian hydrometrical network. As already mentioned, the studied sector extends between the hydrometric stations of Baziaș, in the western extremity, at the entrance of the Danube River in Romania (at km 1,072 away from its mouth) and Ceatal Izmail in the eastern extremity of the studied sector (at 80 km from the Danube's mouth). In Romania and in some publications (e.g. [58, 59, 67, 69]), Ceatal Izmail is named Ceatal Chilia. Between the two extreme stations, we also considered some intermediate hydrometric stations located in key positions, namely upstream of the main tributaries of the Danube River, as follows (Fig. 2): Gruia h.s., located downstream the HENS Iron Gates II, controlling the western part of the studied sector; Bechet h.s., situated downstream of the Jiu River mouth (the most important tributary in the western half of the Lower Danube River); Turnu Măgurele h.s., situated at 82 km away from Bechet, downstream of the confluences with the tributaries Olt (in Romania), and Osam in Bulgaria; Oltenița h.s., located downstream of the Argeș River mouth; Brăila and Grindu hydrometric stations, situated before and respectively after the embouchure of the Siret River, the largest tributary of the Lower Danube River (in terms of discharge and area of its catchment). The last h.s. (Ceatal Izmail), is located downstream of the Prut River mouth (the third largest tributary of the Lower Danube River) and just before the beginning of the delta. Data on the gauging stations are presented in Table 2, and their location is shown in Fig. 2.

The processed data include values of the average, maximum and minimum discharges (annual and monthly) covering different time-periods:

- 1840–2012 for the average multiannual discharges at all selected stations; the data were extracted from [28];
- 1931–2016 for the maximum and minimum multiannual discharges at Baziaș, Gruia, Giurgiu, Oltenița, Brăila and Ceatal Izmail; the data were extracted from [69];
- 1931–2019 for the annual average, maximum and minimum discharges at Baziaș, Oltenița and Ceatal Izmail;

Table 2 Data on the analyzed hydrometric stations

Hydrometric station	Altitude (m.a.s.l.)	Distance from the Danube R. mouth (km)	River basin area (km^2)
Baziaș	64	1,072.4	570,896
Gruia	29	851	580,100
Bechet	22	679	603,586
Turnu Măgurele	19	597	654,000
Oltenița	16	429.7	684,803
Brăila	1	169.4	726,000
Grindu	0.8	139.6	775,500
Ceatal Izmail	0.6	79.6	776,883

Source NARW database

– 1976–2019 for the monthly average, maximum and minimum discharges at Baziaș, Oltenița and Ceatal Izmail.

For the last two periods, the data come from the National Administration Romanian Waters (NARW) database, which includes the National Institute of Hydrology and Water Management (NIHWM) and Water Basin Administrations (WBAs) databases.

Based on the streamflow data, classical statistical parameters (e.g. minimum, average, maximum, coefficient of variation) were computed for different time-scales and their spatio-temporal variability was analyzed. The linear trends in the variation of streamflow were investigated by using the statistical non-parametric test of Mann-Kendall coupled with the non-parametric Sen's method for the magnitude of the trend. The level of significance (α) of the identified trend was considered at 0.001, 0.01, 0.05 and 0.1 [70]. To identify possible influences of the Iron Gates I and II hydroelectric systems on the Danube's flow, comparisons of flow parameters between the periods pre- and post-commissioning of the systems were performed.

4 Spatial Variation of the Multiannual Flow

In this section we investigated the long-term variation of the average, maximum and minimum discharges along the LDR.

To highlight the features of the Danube's **average flow** variation, we analyzed the multiannual discharges recorded at gauging stations located at the beginning and end of the studied sector (Baziaș and respectively Ceatal Izmail), as well as data from several intermediate stations: Gruia, Bechet, Turnu Măgurele, Oltenița, Brăila and Grindu. The analyzed period covers more than 170 years (1840–2012). The data were extracted from [28] and were indirectly estimated, by extending the length of the data series on daily levels and discharges measured at gauging stations located on the Lower Danube River (as shown in [57]). Even if these estimated data are not officially validated, due to the very long period, in the case of the multiannual average flow, the errors (resulted by comparing the estimated and recorded discharges) are reduced. Consequently, we considered that the results reflect well the real situation at the selected stations.

As expected, the average multiannual flow of the Danube increases from upstream to downstream, as the basin area and the input of tributaries grow. Thus, there is an increase between the two extreme stations of almost 1,000 m^3/s (namely 934 m^3/s), from 5,551 m^3/s at Baziaș, to 6,516 m^3/s, at Ceatal Izmail (Fig. 3). The most important difference between successive stations occurs between Brăila and Grindu hydrometric stations (about 260 m^3/s) due to the significant contribution of the Siret River. An important flow increase is also noticed between Bechet and Turnu Măgurele gauging stations (about 210 m^3/s). In this sector the Danube River receives its second largest tributary in the lower course (Olt River, on the left side) and a few smaller tributaries on the right side (e.g. Iskar, Vit, Osam). Upstream Gruia h.s., although