DEFINING A WATER-ENERGY-FOOD NEXUS FRAMEWORK FOR WATER ALLOCATION IN THE LOWER DANUBE BETWEEN IRON GATES AND ZIMNICEA

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DOI: 10.5281/zenodo.7491459

Abstract. Water consumption is rising due to global population growth, climate change, and other socioeconomic factors. The race to extract more water to meet the demands of various sectors is intensifying, making equitable water allocation challenging. An effort was made in this study to assess the water supply and demand gap among several sectors, namely energy, agriculture, and navigation in the lower Danube stretch, where water is shared by Serbia, Romania, and Bulgaria. The main study was conducted on water allocation needs for various sectors. To understand the water supply and demand balance under different conditions, three alternative scenarios were generated: dry, normal, and wet year periods. The Water Evaluation and Planning Model (WEAP) software tool was used to estimate the demand and supply gap in the research area for both energy production and irrigation, and a hydraulic model was used to determine the water depth corresponding to the flow remaining in the river after the withdrawals for energy and irrigation. The hydraulic model was based on the US Army core of Engineers tool HEC-RAS. In terms of water demand for energy production, the findings indicate that over a calendar year, the highest water demand is fulfilled during the month of April, while September has the lowest demand fulfilment. No water deficit has been found for agriculture water use in any of the defined scenarios, given the fact that available water in the system is much higher than the required crop water requirement (cwr) throughout the year. According to the hydraulic model results, water depth is rather low in dry years, which will have a detrimental impact on navigation.

Key words: water allocation, planning, hydraulic modelling, crop water requirement, lower Danube, WEAP, HEC-RAS

1. INTRODUCTION

Water demand is noticeably increasing as a result of global population growth, climate change, and socioeconomic factors, such as industrial development, improved sanitation, and domestic waste management (Ferroukhi *et al.*, 2015). The global population has grown from 3.03 billion in 1960 to 7.38 billion in 2015 (Roser *et al.*, 2013). To support this rising population, agricultural production tripled between 1960 and 2015 by employing chemical fertilizers and pesticides, regulating water supplies, and adopting new farming practices such as mechanization (FAO, 2017). This took a significant amount of water and energy. Agriculture is the major user of the global water supply, accounting for an average of 70% of all global water withdrawals (Postel and Vickers, 2014). The world population is expected to reach 9 billion people by 2050 if current trends continue (Cole *et al.*, 2018). Feeding this population will necessitate a 60% increase in food production over 2015 (Bene *et al.*, 2015).

Nexus thinking evolved out of an awareness that natural resources are beginning to constrain economic growth and human well-being objectives significantly. The pressure on resources may eventually result in shortages, jeopardizing people's access to water, energy, and food, impeding economic development, causing social and geopolitical tensions, and wreaking irreversible environmental damage (Hoff., 2011). Identifying the connections between critical natural resource sectors and collectively increasing their efficiency was deemed a win-win strategy for human well-being and environmental sustainability for current and, more crucially, future generations (Ali *et al.*, 2019).

Equitable water allocation is an important field of research considering the current climate change effects. In light of population growth and climate change, it is crucial to determine the current water supply and demand gap among different sectors and its future evolution. Several studies have been conducted to examine water resource allocation under different scenarios. Mirdashtvan *et al.* (2019) researched how to optimize the available water resource allocation based on the Representative Concentration Pathways (RCPs) in the south Alborz region of Iran. Similarly, Adgolign *et al.* (2015) investigated surface water resource distribution in West Ethiopia's Didessa Sub-Basin by developing a WEAP model. However, less work has been done so far to analyse water distribution using the WEFN approach.

Europe, a major contributor to greenhouse gases, is currently facing threats from human-induced climate change. According to estimates from the European Environment Agency (EEA), about one-third of Europe's territory is subject to water stress conditions, either temporarily or permanently (EEA, 2018). Water scarcity is projected to become increasingly common as a result of climate change. The Danube River catchment, in which more than 80 million people leave, is going through water pressure as a result of domestic, industrial, and agricultural activities.

The present study shows the analysis of the current water demand and supply gaps available in energy, agriculture, and navigation in a stretch on the lower Danube under different scenarios considering the water energy food nexus (WFEN) approach. The paper is structured into five sections. After this introduction, the case study is presented, followed by the methodology applied to carry out the research. Section four present results and discussion, followed by section five with conclusions.

2. CASE STUDY DESCRIPTION

With an extent of 801,463 km^2, the Danube River Basin is one of the largest river basin in Europe. The Danube catchment area is home to more than 80 million people from 18 countries, making it the world's most international river basin (ICPDR, 2019). Research presented herein focuses on a 420 km stretch long of the lower Danube River, starting at Dubova, (located 24 km upstream of Iron Gate I) and ending downstream of Bujoru, Romania (Fig. 1). The research area's major streams, infrastructure, and relatively big towns are also represented in Figure 1. From the overall considered area, 53% is in Romania, 41% in Bulgaria, and the remaining 5% is located in Serbia.

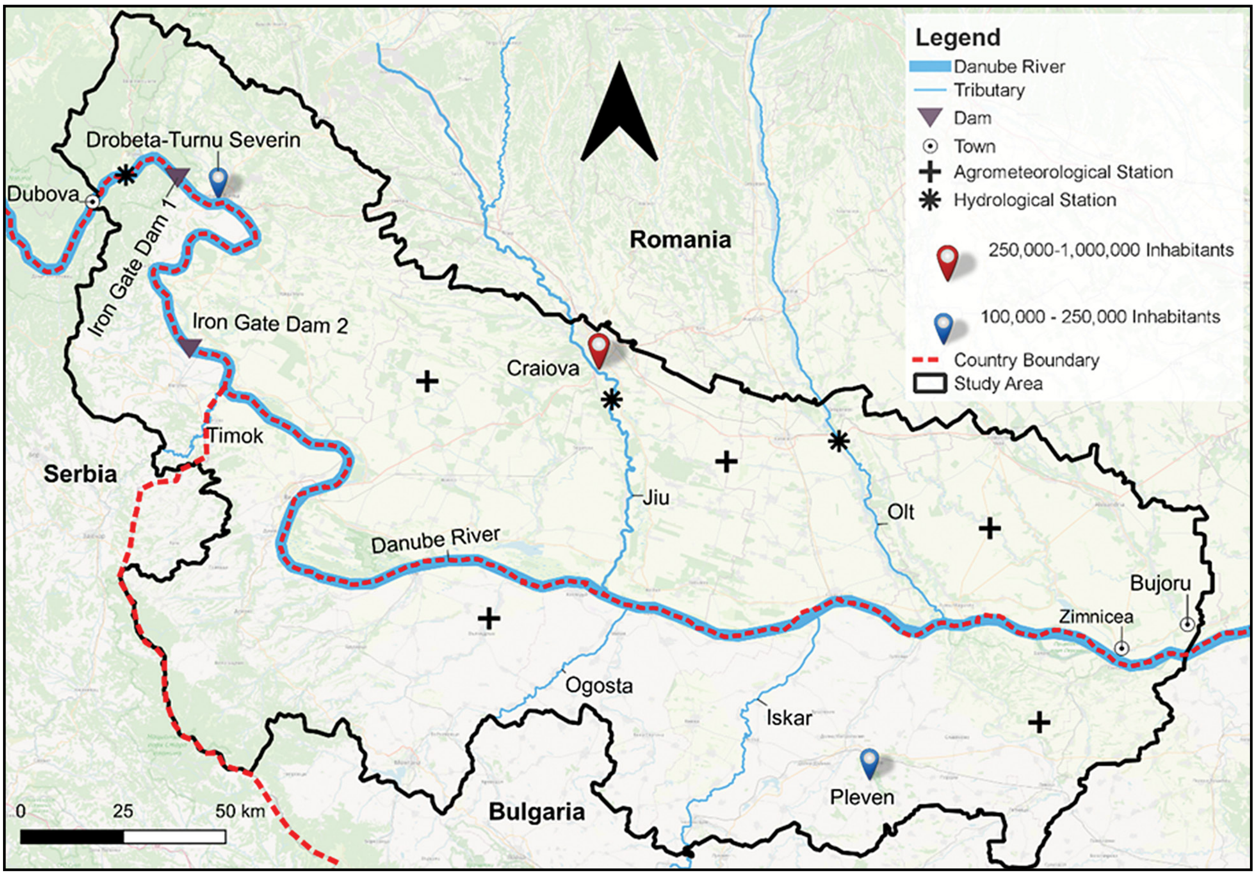


Fig. 1. Studied stretch of the Lower Danube River.

The climate in the area is a transitional temperate-continental with oceanic influence from the West, Mediterranean effects from the South-West, and excessive continental influences from the East. The average temperature is higher in the summer months of July and August with over 20 degrees Celsius, while the lowest is in the winter months of December and January (Fig. 2). The annual precipitation averages 637 millimetres (mm) and decreases in intensity from West to East, from over 600 mm to less than 500 mm on the East Romanian Plain, to about 350 mm towards the coast, however, it can reach 1000 –1500 mm on hilly places. In the considered stretch of the Danube, the average discharge is 5,420 m^3/sec, ranging from 7,930 to 3,730 m^3/sec in wet and dry years, respectively (Comoglio, 2011).

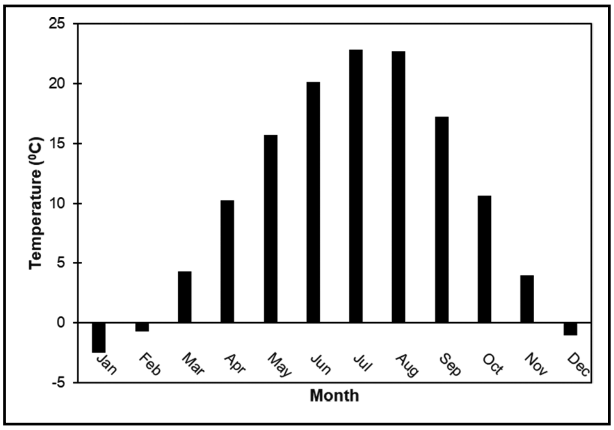


Fig. 2. The average temperature of the lower Danube Basin. Data Source: NASA, POWER.

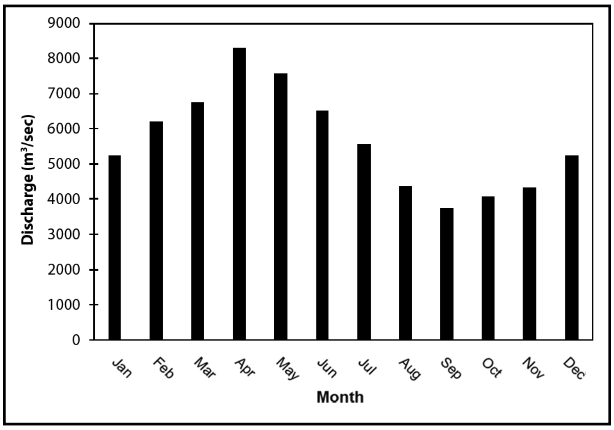


Fig. 3. Average discharge of in the studied stretch. Data Source: Global Runoff Data Center (GRDC).

Based on the land use of the area on the study, as presented in Figure 4, agriculture dominates the land use land cover in the research area, with crops covering 63% of the total area under study. The second land cover type is vegetation, accounting for 19% of the surface area, mostly in the northwestern part of the area, followed by 11% bare land, 5% built-up areas, and 2% water bodies, as indicated in the Table 1.

Table 1. Land cover type and its relative percentage of the total area.

Type of land cover	%
Agriculture	63
Vegetation	19
Bare land	11
Built Area	5
Water bodies	2

The study area is home to one of Europe's largest hydroelectric power dams, Iron Gate I and II, with a total water storage capacity of 2400 million m^3, shared by Serbia and Romania. These are primarily utilized for base hydropower generation, flow regulation for navigation purposes, and industrial water supply. The hydroelectric facilities have a combined capacity of 2,532 MW with an annual production of 13,140 GWh (Comoglio, 2011).

From a navigation point of view, the research area lies along a key route, connecting most European countries to the Black Sea. Romania has the greatest portion of the Danube, accounting for about a third of the total river length. Inland navigation in Romania has gained much importance, transporting over 20% of all cargo in 2011, rising from the approximately 10% of in the previous decades (Scholten & Rothstein, 2016).

The study area is characterized by the presence of various ecological services. Considering the importance of the ecosystem services (ES), 21% of the study area, falls in the protection zone based on the Natura2000 regulation, which needs to be protected to provide ecosystem services in the long run. The wetlands contribute to food security by increasing aquaculture production, resulting in improved community well-being. Besides enhancing biodiversity and attracting eco-tourists, wetlands also play a vital role in reducing flood risk. However, the sectoral policies, i.e. energy production, flood protection, ecosystem regeneration, fish farming, agricultural production, and navigation, have adversely affected the potential to provide sustainable ES. In the past (seventies), the government decided to drain wetlands to boost agricultural production. Currently, a significant portion of the former riparian wetlands is used either for agricultural production or as pasture. However, not all wetlands were dried up, and some area with limited connection to the Danube, is still present, showing poor condition from an ecological point of view (Pagano *et al.*, 2022).

All the previous identified involved sectors (i.e. energy, agriculture, and navigation) create socioeconomic opportunities and are equally important. However, the sectoral policies of energy production, irrigation, and navigation in the lower Danube river downstream of the Iron Gates had a long-term negative impact on the engaged sectors (Pagano *et al.*, 2022).

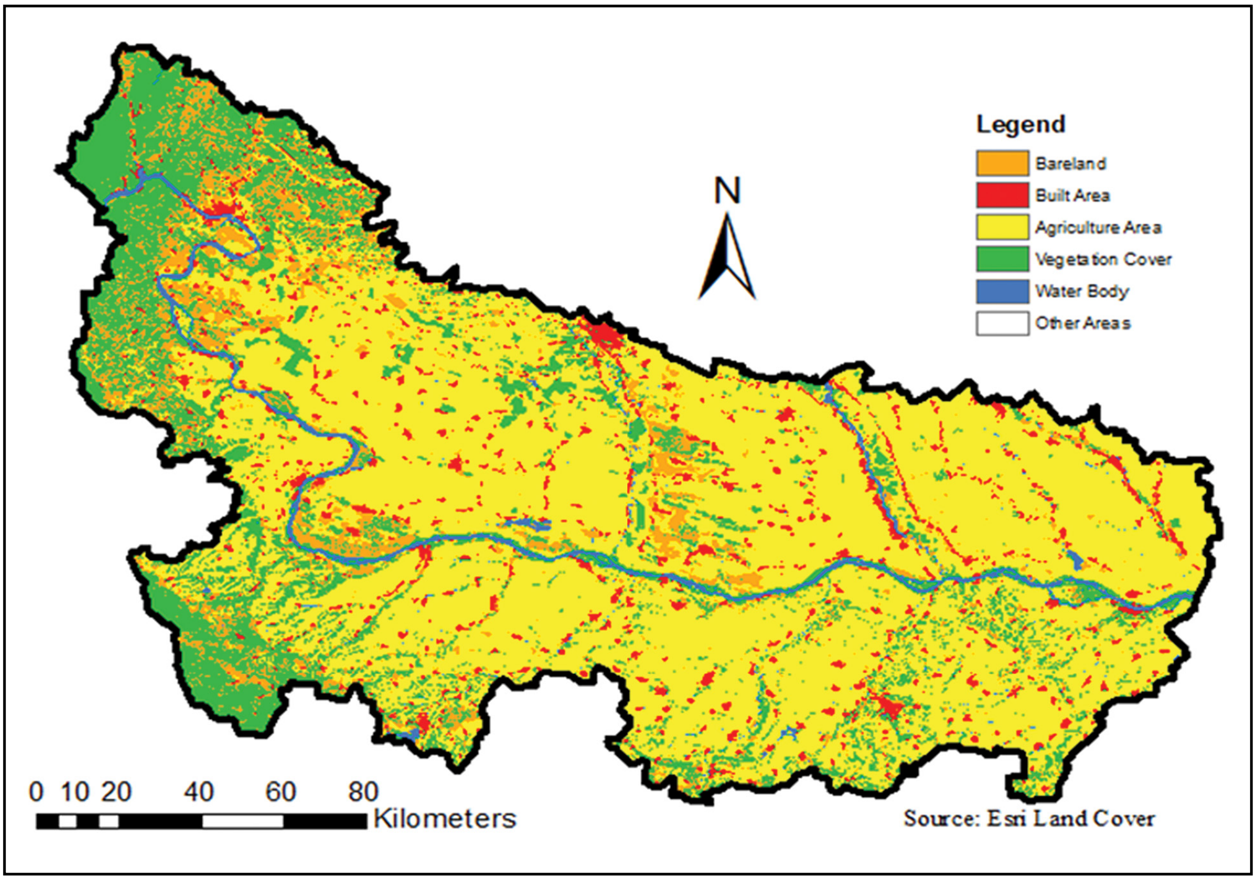


Fig. 4. Land use land cover map.

Therefore, there is a need for a paradigm shift from a sector-centered to a holistic approach to maximize water usage while having no detrimental impact on other sectors. So far, very little research has been conducted on the water use of different sectors in this region. This reveals a significant gap in the knowledge required for effective water allocation among various sectors.

3. MATERIAL AND METHODS

The overarching objective of the study is to examine the water use by energy, agriculture, and navigation in the lower stretch of the Danube river in different flow years and analyze how the upstream water consumption in the area affect the downstream navigation.

To address the intended objective of this study, the conceptual framework (Fig. 5) was followed, beginning with data collection from several sites and portals as described in the preceding section. Geospatial and agro-meteorological analyses were carried out independently to create input data for the Water Evaluation and Planning (WEAP) model. The WEAP model was initially run under normal flow conditions or during a normal year. In addition to the normal flow condition, the model was run with two scenarios based on high and low flows to study how water demand and supply differ in extreme flow conditions. Following the water allocation model, a hydraulic model in HEC-RAS was built to determine the depth at predefined cross-sections of the main Danube river. The following section provides brief explanations of the main approaches.

3.1. Crop Water Requirement (CWR)

Using the Smith approach of CROPWAT (1992), which is a decision support tool developed by the Land and Water Development Division of Food and Agriculture Organization (FAO). CROPWAT is a computer program which calculates crop water requirements (cwr) based on soil, climate and crop data. The net irrigation demand for each crop during the growing season is computed as the difference between the effective precipitation and potential evapotranspiration as follows:

$$I_{net} = E_{cpot} - P_{eff} = K_c \times E_{pot} - P_{eff} \quad \text{if} \quad E_{cpot} > P_{eff} \quad (1)$$

$$I_{net} = 0 \quad \text{if} \quad E_{cpot} \leq P_{eff} \quad (2)$$

where,

I_{net} = irrigation requirement per unit area [mm/d]

E_{cpot} = crop-specific potential evapotranspiration [mm/d]

P_{eff} = effective precipitation [mm/d]

E_{pot} = potential evapotranspiration [mm/d]

K_c = crop coefficient [dimensionless].

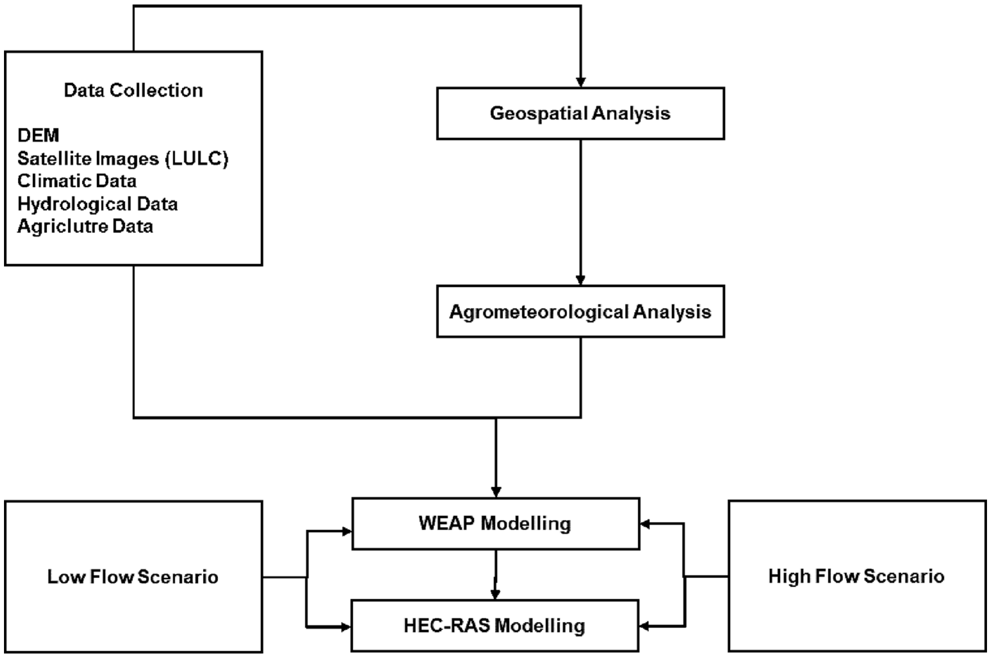


Fig. 5. Conceptual Framework for water- food- energy nexus analysis.

Effective precipitation (P_{eff}) is the portion of the total precipitation that does not runoff and is available for crop growth. P_{eff} is extremely difficult to determine in the absence of detailed site-specific details. In this study, an approximation method of the U.S. Department of Agriculture Soil Conservation Method as mentioned by Smith (1992) is used.

$$P_{eff} = P\frac{(4.17 - 0.2P)}{4.17} \quad \text{for} \quad P < 6.3\frac{\text{mm}}{\text{d}} \tag{3}$$

$$P_{eff} = 4.17 + 0.1P \quad \text{for} \quad P \geq 8.3\frac{\text{mm}}{\text{d}} \tag{4}$$

The CRW is calculated for the six key crops grown in the study area: wheat, maize, watermelon, tomatoes, cucumbers, and peppers. The growing season of each crop is defined using the United States Department of Agriculture (USDA) Foreign Agriculture Service portal (Fig. 6).

The crop coefficient (Kc) values for various crops are determined by crop stage. Figure 7 shows Kc values for the indicated crops in the study are defined using the AQUASTAT climatic information tool. For all considerred crops the values of Kc increase with time during the crop development stage, followed by a constant value in the middle stage, and then a rapid decline during the ripening period.

3.2. The WEAP Model

Water Evaluation and Planning (WEAP) system was developed by the Stockholm Environment Institute (SEI), primarily for water resource planning. It provides a comprehensive, versatile, and user-friendly framework for water planning and strategy analysis. It acts as a management system for water use and demand data. It can model water demand and supply, runoff, storage amount, pollution sources, evaporation rates, and river water quality.

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wheat	■	■	■	■	■	■	■			■	■	■
Maize				■	■	■	■	■	■			
Watermelon				■	■	■	■	■				
Tomatoes				■	■	■	■	■				
Cucumber				■	■	■	■	■				
Pepper				■	■	■	■	■				

Fig. 6. The growing seasons of the identified crops in the study area. Source: USDA Foreign Agriculture Service.

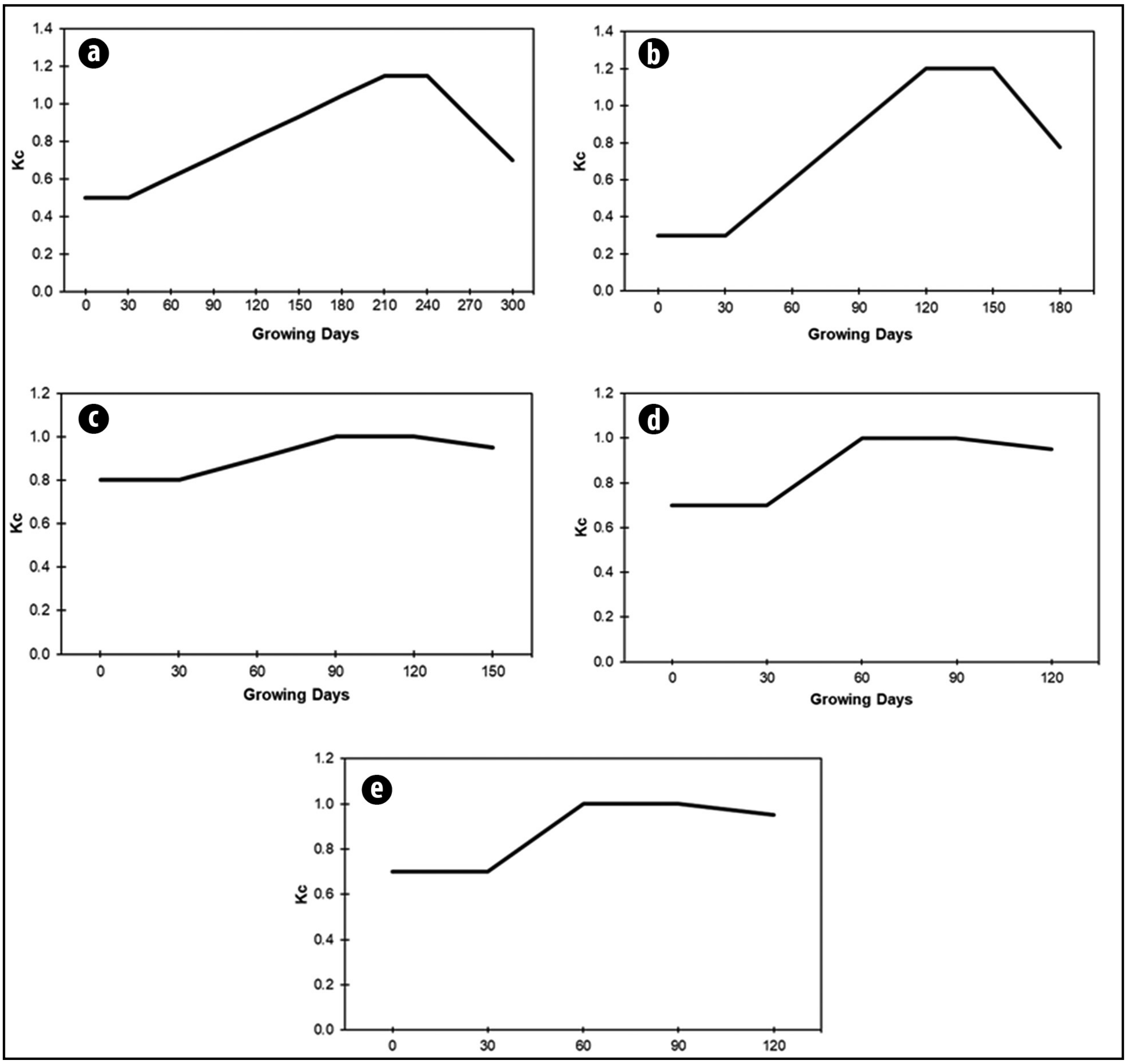


Fig. 7. Crop Coefficient (K_c) values for (**a**) Wheat, (**b**) Maize, (**c**) Water Melon, (**d**) Tomatoes & Cucumber, and (**e**) Pepper.

The river network schematization used to set-up the WEAP model of the study is the one comprised within the case study boundaries, represented by the Danube River and its tributaries, Jiu, Olt, Timok, Ogosta, and Iskar. Figure 8 shows the WEAP model the study area, which includes five agricultural demand locations, three of which are in Romania and the other two in Bulgaria. Serbia was not assigned a demand site due to its small size within the study area.

The storage capacity of IG I and II are represented in the WEAP model as 2,400 million m^3 and 830 million m^3, respectively. These volumes are based on FAO data as recorded by Comoglio (2011). Iron Gates I hydropower station has 12 installed turbines, each functioning at a maximum discharge of 840 m^3/sec, hence for a maximum energy production the station would require a total discharge of 10,800 m^3/sec. Similarly, IG II require 9,500 m^3/sec, as it has 20 turbines installed, each of which using a maximum discharge of 475 m^3/sec. Both IG I and IG II reservoirs are designed to function as a run-off river system, not to store water for a long time period.

According to the carried out geospatial analysis, agricultural land accounts for 63% of the total area or 1.83 million hectares. In view of missing published data regarding the crops cultivated in this area, this study assumed the crop grown based on the LU/LC of the year 2017. The most common cereals crops in the study area are winter wheat and maize, hence assumed for 30% and 29% of the total agriculture area, respectively. Similarly, watermelon is the most common type of fruit crop, assumed for 10% of the agricultural land, followed by tomatoes and cucumbers (11%), and peppers (9%) (Table 2).

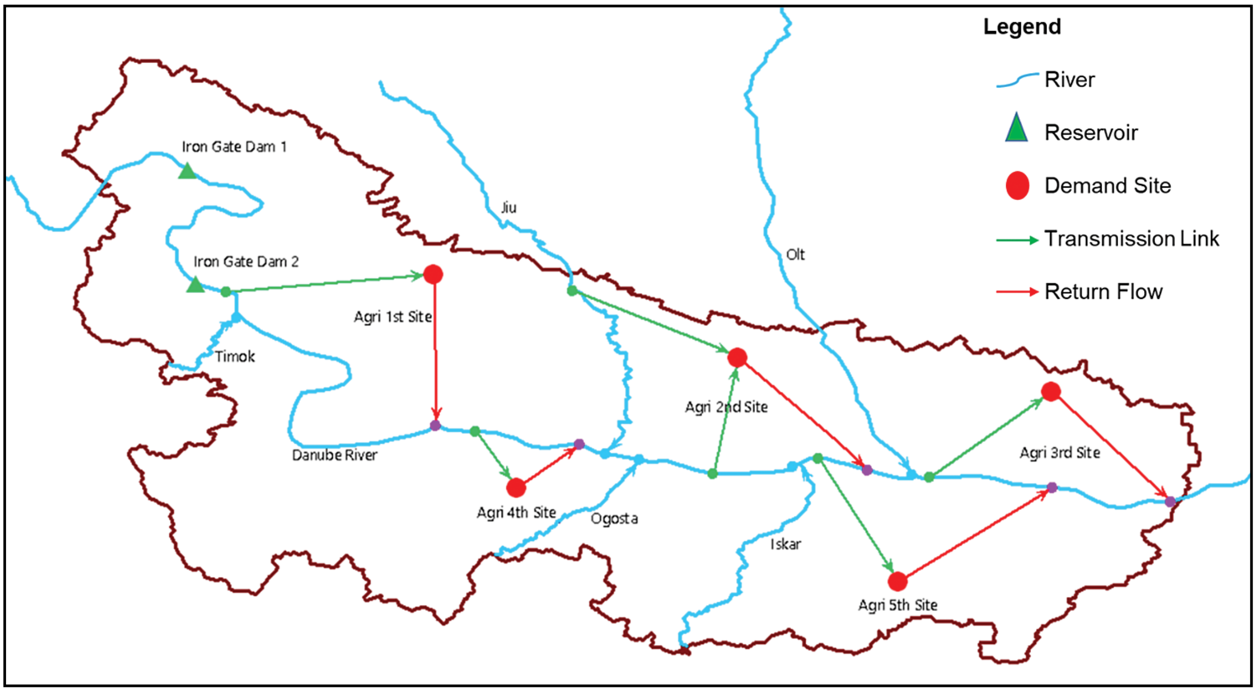


Fig. 8. Setup of the WEAP model, in which the points of agricultural demand are represented.

Table 2. Crop type and its relative area

Crop Type	Cropped Area (%)
Wheat	30
Maize	29
Tomatoes	11
Cucumber	11
Watermelon	10
Pepper	9

Following the crop calendar, the cropped areas on agricultural land vary by month during a calendar year. Figure 9 shows that the entire agricultural land is only cultivated for four months, spanning from April to July. In contrast, during the remaining months of the year, approximately one-third of the land is cultivated.

Based on the assumed annual activity values for each crop in the study area, the annual water use rate was calculated using equations (1) – (4). The obtained annual water consumption rate of each crop is shown in Table 3.

Table 3. Annual crop water requirement

Crop Type	Water (CWR) M^3/Ha
Wheat	2151
Maize	3658
Tomatoes & Cucumber	2025
Watermelon	3029
Pepper	2057

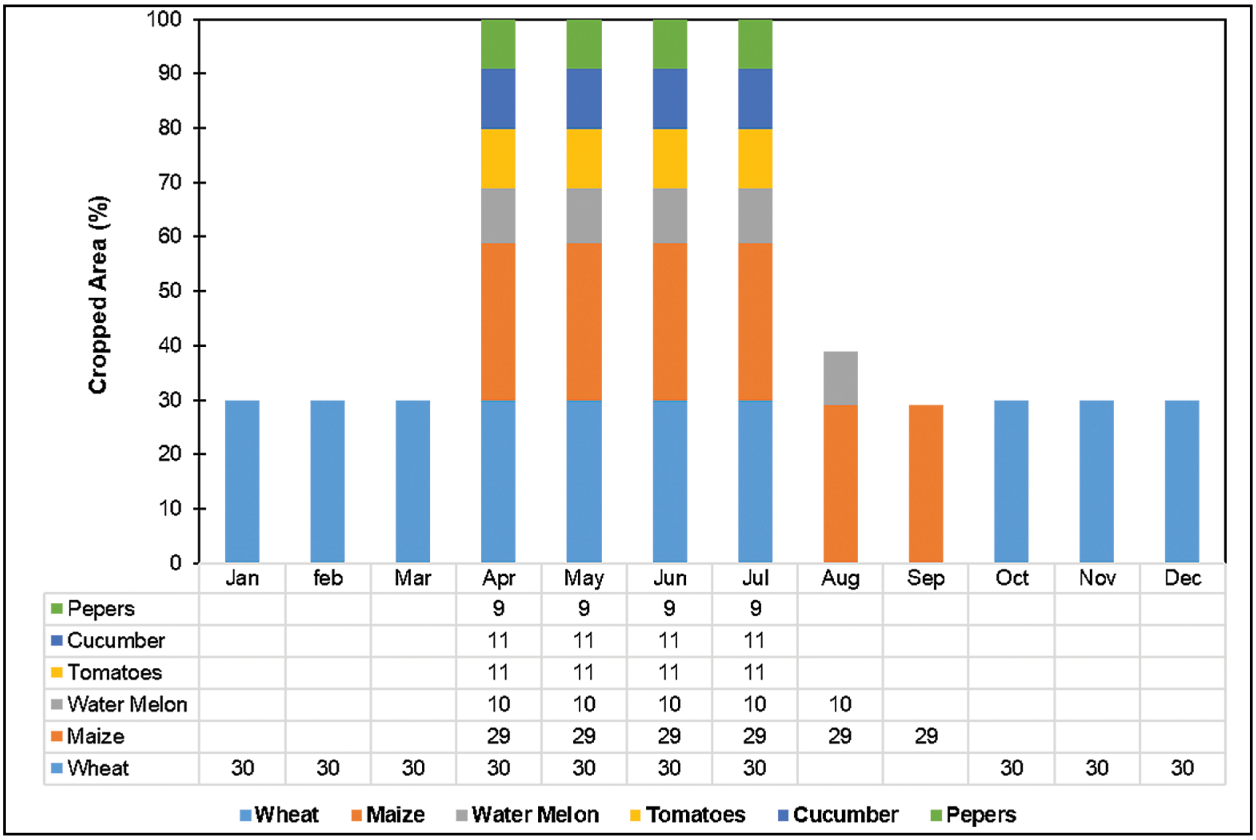
Four of the five agricultural water demand sites are linked to the main Danube river through a single transmission link and a single return flow link. Alongside the Danube, only agricultural site 2 is connected to the Jiu tributary via an extra transmission link. Priority 1 is assigned to all designated agricultural sites, which means that the demand site's priority for supply take precedence over all other water demands in the system. The simulation time of the model was January 2017 to December 2021. The current account year is 2017, and all essential data has been added to this year.

3.3. The HEC-RAS Model

The Hydrological Engineering Center's River Analysis System (HEC-RAS), developed by the US Army Corps of Engineers is used for conducting analysis for one-dimensional steady flow, one and two-dimensional unsteady flow, sediment transport computations, and water quality models.

In this study the 5.0.7 HEC-RAS version was used to compute the river water depth by modelling the one-dimensional unsteady flow in the Danube river. To accurately reflect the river, 114 cross-sections were represented along the Danube, with an average distance of 3.6 kilometres between each other. Manning's Roughness Coefficients, published by Engineering Toolbox (2004), recommend a roughness coefficient of 0.030 for the main channel when considering an earthen channel with vegetation. An estimated value of 0.60 was considered for the floodplain.

To model the river, two boundary conditions were set. Flow hydrograph is the upstream boundary condition for the Danube river (Fig. 10).



	Jan	feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pepers				9	9	9	9					
Cucumber				11	11	11	11					
Tomatoes				11	11	11	11					
Water Melon				10	10	10	10	10				
Maize				29	29	29	29	29	29			
Wheat	30	30	30	30	30	30	30			30	30	30

Fig. 9. Monthly distribution of the cropped area.

The flow of the Jiu and Olt rivers (Fig. 11) was added as lateral flow at the intersections with the Danube. Based on the Danube's slope downstream of Zimnicea, a normal depth of 0.00005 was set as the downstream boundary condition.

To compute the flow, the simulation time was set from 02 Jan 2017 to 04 Dec 2017. The computation time step was set to 1 minute, while the other three settings i.e. hydrograph output interval, mapping output detail, and detailed output interval, were set to one day. The model was configured to execute geometry pre-processor, unsteady flow simulation, post-processor, and floodplain mapping programs.

3.4. Scenario Development

To investigate how the extreme flow conditions will affect the water distribution pattern across the engaged sectors, two scenarios of low and high flows (i.e. discharge) were developed. In WEAP configurations, the model was first executed using the average water year, currently set to 2017 and reference accounts from 2018 to 2021. Given the fact that the average flow rate on the Danube is 5,420 m^3/sec, varying between 7,930 and 3,720 m^3/s in wet and dry years, respectively (Comoglio, 2011). Therefore, the dry year was defined as a 0.68 fraction of the normal average flow year, and the wet year is 1.46 times more than the normal year.

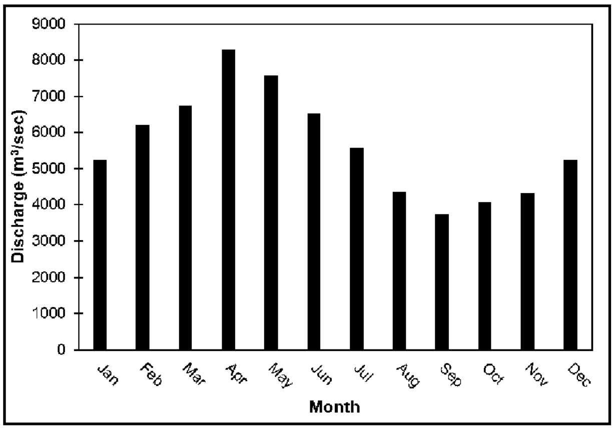


Fig. 10. flow boundary condition for the Danube river in HEC-RAS Model.

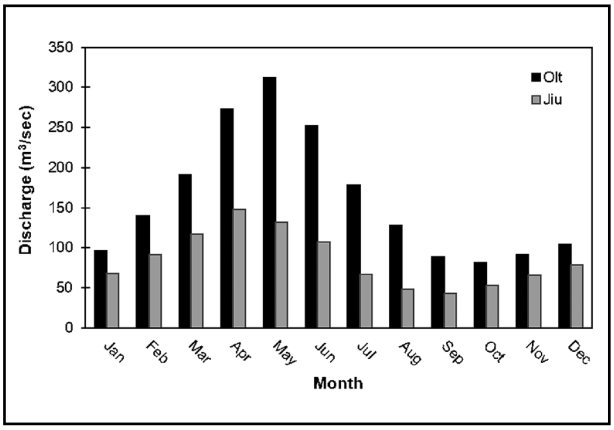


Fig. 11. Lateral flow on Danube in HEC-RAS Model.

3.5. Data Availability

The data used to conduct this analysis was publicly available at: AQUASTAT, Global Runoff Data Center (GRDC), Esri (or Land Cover maps); and USGS.

The agrometeorological data was collected using the AQUASTAT Climate Information Tool, developed by the Food and Agriculture Organization of the United Nations (UNFAO). Five distinct areas as shown in Figure 1 were considered to be the representative crop area for which data was collected. Analysed data from AQUASTAT contains the average monthly precipitation, reference evapotranspiration, and crop coefficient for the identified crops in the study area. The unit of used data and time periods are shown in Table 4.

The average monthly discharge data were obtained from the Global Runoff Data Center, operating under the World Meteorological Organization (WMO). This study employed data from three hydrological stations (see Fig. 1), one located on the main Danube river and two on its tributaries, Jiu and Olt. Table 5 indicates the hydrological data set used in the analysis, as monthly average discharges.

For geospatial analysis, two different datasets were used (Table 6). The land use/land cover (LULC) map was created based on, a 10-meter resolution Geospatial Tagged File Format (GeoTIFF) file for the year 2017. The source of this LULC data is a Sentinel-2 LULC map produced by ESRI.

4. RESULTS AND DISCUSSION

4.1. Energy Demand and Supply Analysis

Following the defined approach, the WEAP model was run under three different water flow conditions, namely normal, dry, and wet flow years, to estimate the water supply and demand gap for the energy production at both IG I and II. Figures 12a, b, and c show the unmet water demand for energy production at IG I in a normal, dry and wet year period. To exploit the full potential of energy production, a discharge of 10800 m^3/sec is required at IG I. In all three scenarios, April is the month with the highest demand fulfilled, while September has the highest water demand deficit. The reservoir operates as a runoff river system without water storage, hence the higher the flow, the greater the demand fulfilment for energy production, and vice versa. The unmet demand decreases constantly from January to April, followed by a steady increase until September, when the water supply is at its lowest. In the months following September, the supply again increases until December.

Although the monthly flow pattern is the same across all three scenarios, with a higher supply in April and a lower supply in September, there is a bigger variation in quantity, showing a higher to lower unmet demand for dry, normal, and wet years, respectively. Figure 13 shows that there is no unmet demand in April in the wet year, while 23% and 48% of unmet water demand were estimated for normal and dry years, respectively. Similarly, a 49% unmet water demand is calculated for the wet year in September, however, around 65% and 76% water deficit exists in the same month for the normal and dry years.

Similar supply and demand imbalances exist for Iron Gate Dam 2. Figures 14a, b, and c indicate the unmet water demand for all scenarios at Iron Gate Dam 2. Given that Iron Gate Dam 2 demands a relatively lower discharge of 9,500 m^3/sec, the unmet demand is lower than that of IG I upstream.

Another significant difference between IG I and II is that no water deficit was recorded in IG II for four months during the wet year (Fig. 15), from March to June, whereas only two months, April and May, have 100% demand fulfilment in IG I.

Table 4. Agro-meteorological data variables and time periods used for analysis

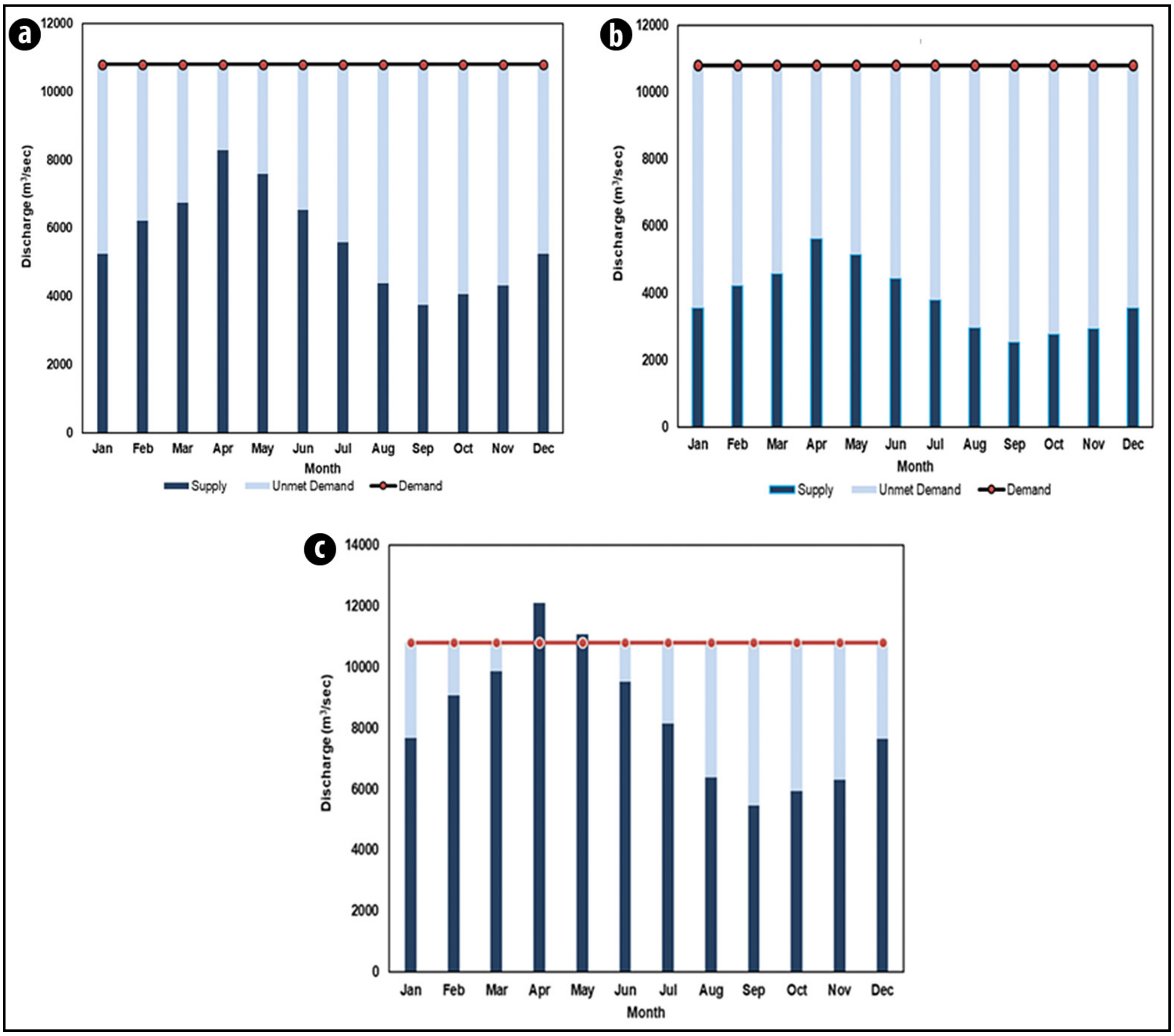
No	Variable	Unit	Time Period
1	Precipitation	mm/month	1960-1990
2	Reference Evapotranspiration (ETo)	mm	1960-1990
3	Crop Coefficient		2022

Table 5. Time extent of the data sets

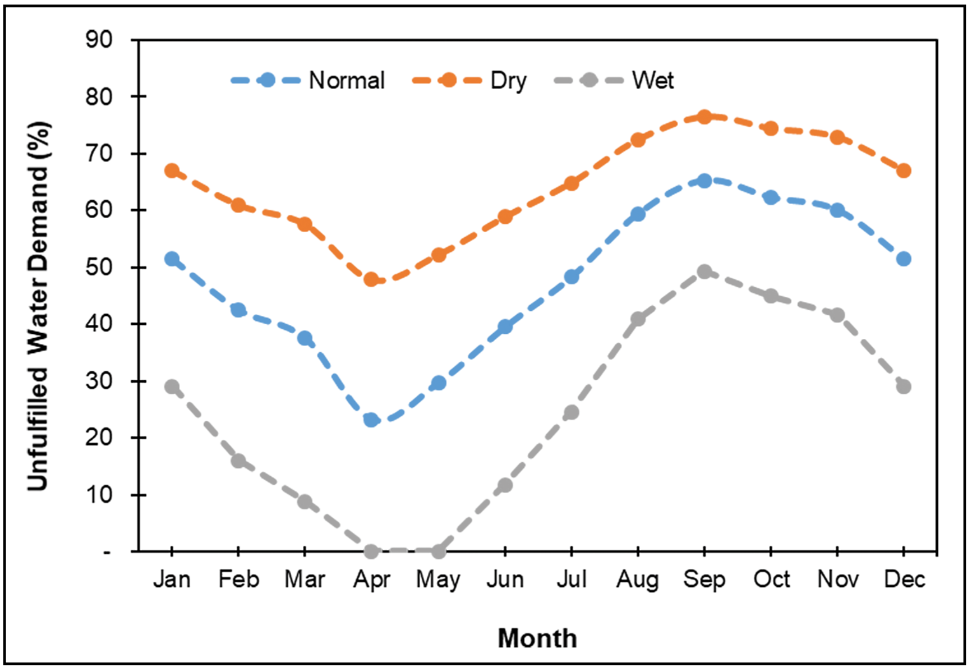
No	River	Station location	Time Period	Frequency of data availability
1	Danube	Orsova	1973-1988	Monthly
2	Jiu	Podari	1950-2008	Monthly
3	Olt	Stoenseti	1950-1970	Monthly

Table 6. Geospatial data

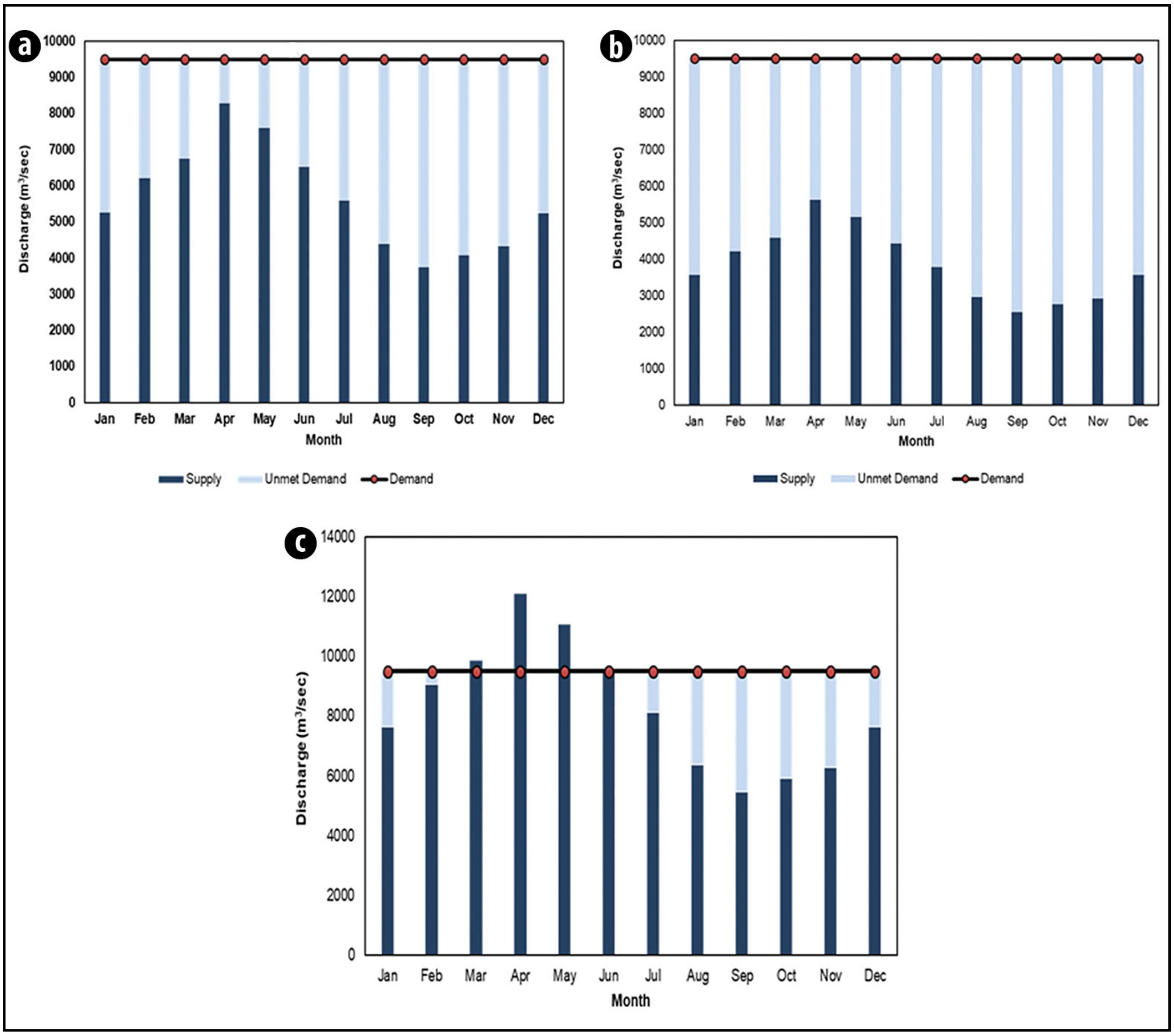
No	Variable	Resolution	Time Period	Data Source
1	Land use land cover	10m × 1 m	2017	Esri Land Cover, 2017
2	Digital Elevation Model	30m × 30m	2017	Earth Explorer, USGS



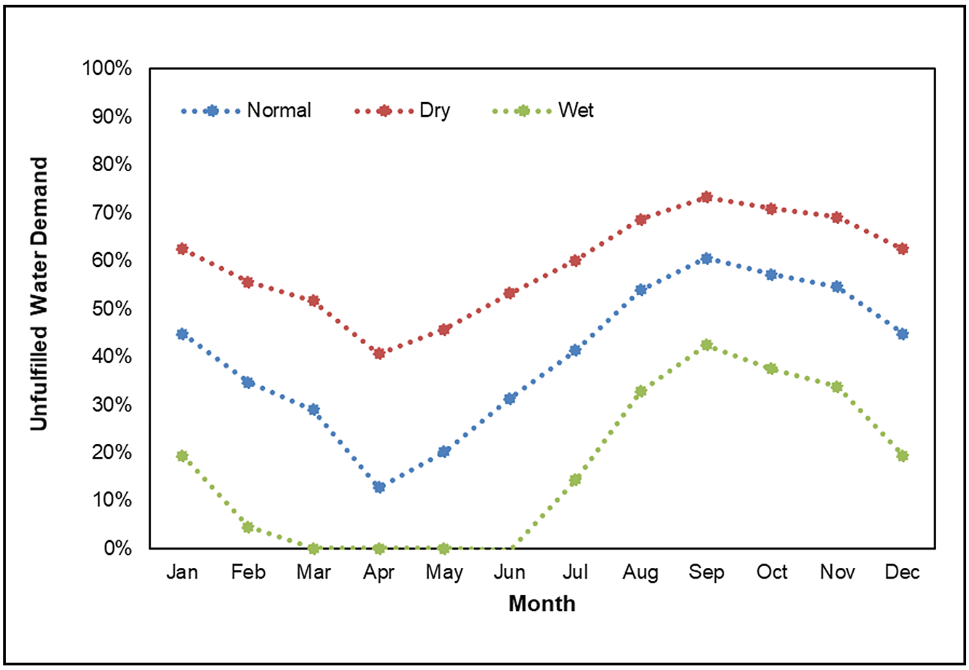
▲ **Fig. 12.** Water supply and demand for energy production in (**a**) Normal flow year, (**b**) Dry flow year, and (**c**) Wet flow year at IG I.



◀ **Fig. 13.** Unfulfilled water demand for energy production in dry, normal and wet year period at IG I.



▲ **Fig. 14.** Water supply and demand for energy production in (**a**) Normal flow year, (**b**) Dry flow year, and (**c**) Wet flow year at IG II.



◀ **Fig. 15.** Unfulfilled water demand for energy production in dry, normal and wet year period at IG II.

4.2. Irrigation Demand and Supply Analysis

Irrigation is the second largest water consumer in the studied area. After determining the water demand for each crop, the total water demand for irrigation in the research area was estimated for each month. Figure 16 depicts the total amount of water necessary to meet the irrigation demand in the study area. The bars in the graph show the quantity of water required by each crop in the selected month, while the line represents the overall amount of water necessary for irrigation in the particular month. June is the month with the biggest water demand, with a flow requirement of 654 m^3/sec, while September is the month with the lowest water demand, with a flow requirement of 83 m^3/sec. From October to March, there is no irrigation water demand due to the absence of crops or the fact that precipitation exceeds the crop's total water consumption.

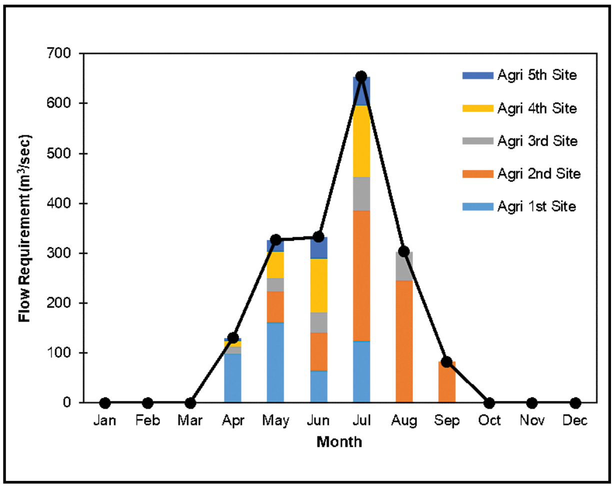


Fig. 16. Total annual crop water requirement (cwr) in the study area.

To analyze the water demand and supply gap for irrigation, the model was run under the same selected three distinct scenarios. Figure 17 shows the available water in the lower Danube river under dry, normal and wet year periods. Throughout the three scenarios, it is seen that all irrigation water requirements were met (Fig. 18), given the fact that flow is significantly greater than the amount of water required for agricultural use.

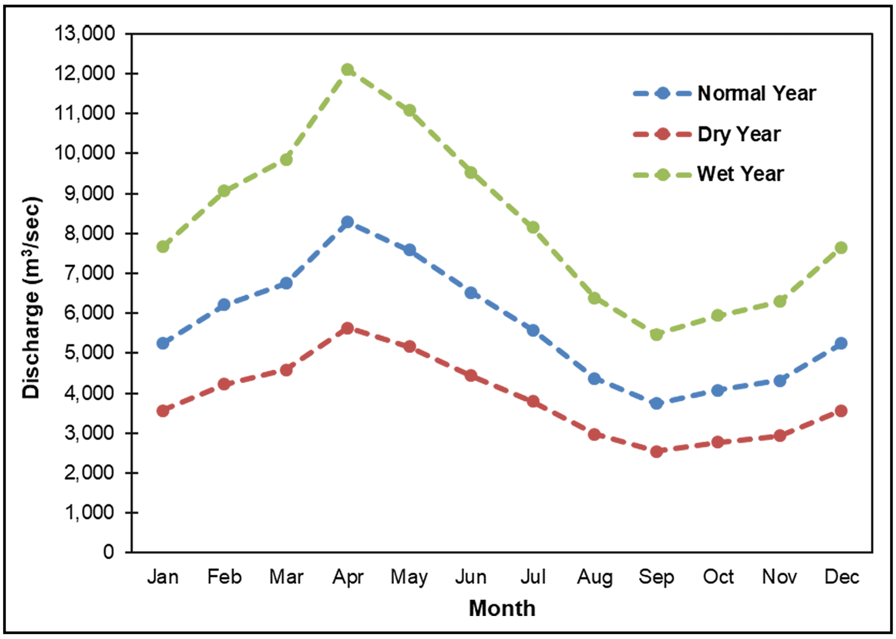


Fig. 17. Flow in the lower Danube river in a normal, dry and wet year period.

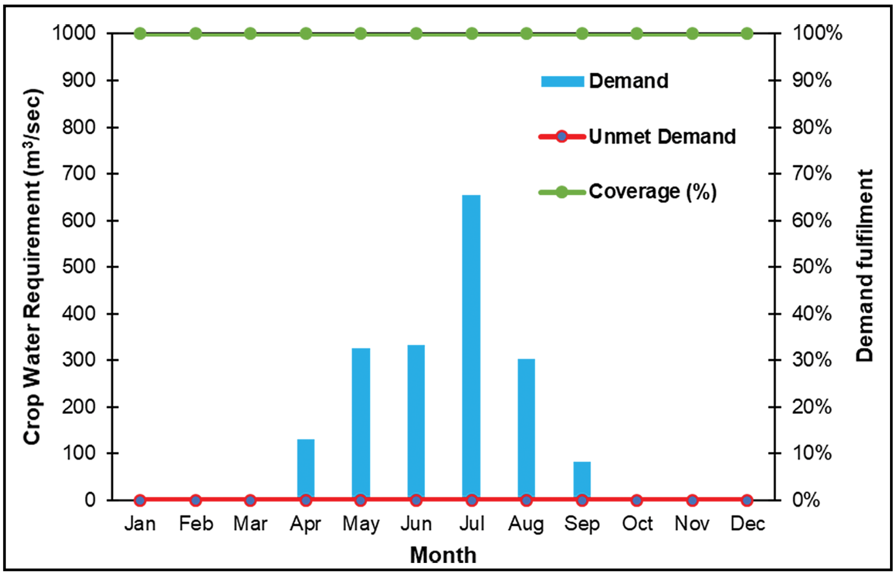


Fig. 18. Demand fulfilment of the irrigation requirement in the study area.

As a result, the coverage percentage is 100%, as indicated by the green line in the graph, and no unmet demand was discovered, as represented by the red line (Fig. 18).

4.3 Navigation Analysis

The water depth along the Danube river was calculated using HEC-RAS flow modelling under the three considered scenarios. The HEC-RAS model shows the variation in water depth in different flow conditions. Figure 19 shows water depths based on the dry year scenario

Three cross-sections were chosen to determine the variation in depths: upstream, middle, and downstream. Figures 20, 21, and 22 show the water depths associated with normal, dry, and wet years. All three graphs show that water depths are steadily increasing from January to April, given the fact that discharge is increasing during this period. April, the month with the highest discharge for the entire period, has relatively higher depths than the other months. After springtime i.e. April, water depths gradually decrease until they reach a minimum in September. This is due to decreasing river discharges and the use of water for agriculture. However, in this case study, agricultural water usage has no significant impact on the water depth of the main river. The variation in depth is highly related to the natural flow variation throughout the year.

Under different flow conditions, the results also show a significant depth variation. The water depths under low flow conditions are considerably lower than in normal and wet year periods, which have a significant impact on navigation. This affects navigation in the area, particularly during the summer and autumn months, which span from July to November.

5. CONCLUSIONS AND RECOMMENDATIONS

An effort was made in this study to analyse how water is used in the lower Danube river among various sectors, including energy, irrigation, and navigation. To begin with, an investigation was conducted to understand the characteristics of the research area and to highlight the core water issues associated with this region. To answer the intended research questions, a set of approaches were used establishing a water allocation model using the Water Evaluation and Planning (WEAP), and designing a hydraulic model in HEC-RAS were used. Data were collected and processed from remote sensing and globally available data from online portals, Geospatial and agro-meteorological analyses were undertaken independently to generate input data for the WEAP model. The WEAP model was initially run under normal flow conditions or during a normal year. In addition to the typical condition, the model was run with two scenarios based on high and low flows to investigate how water demand and supply vary.

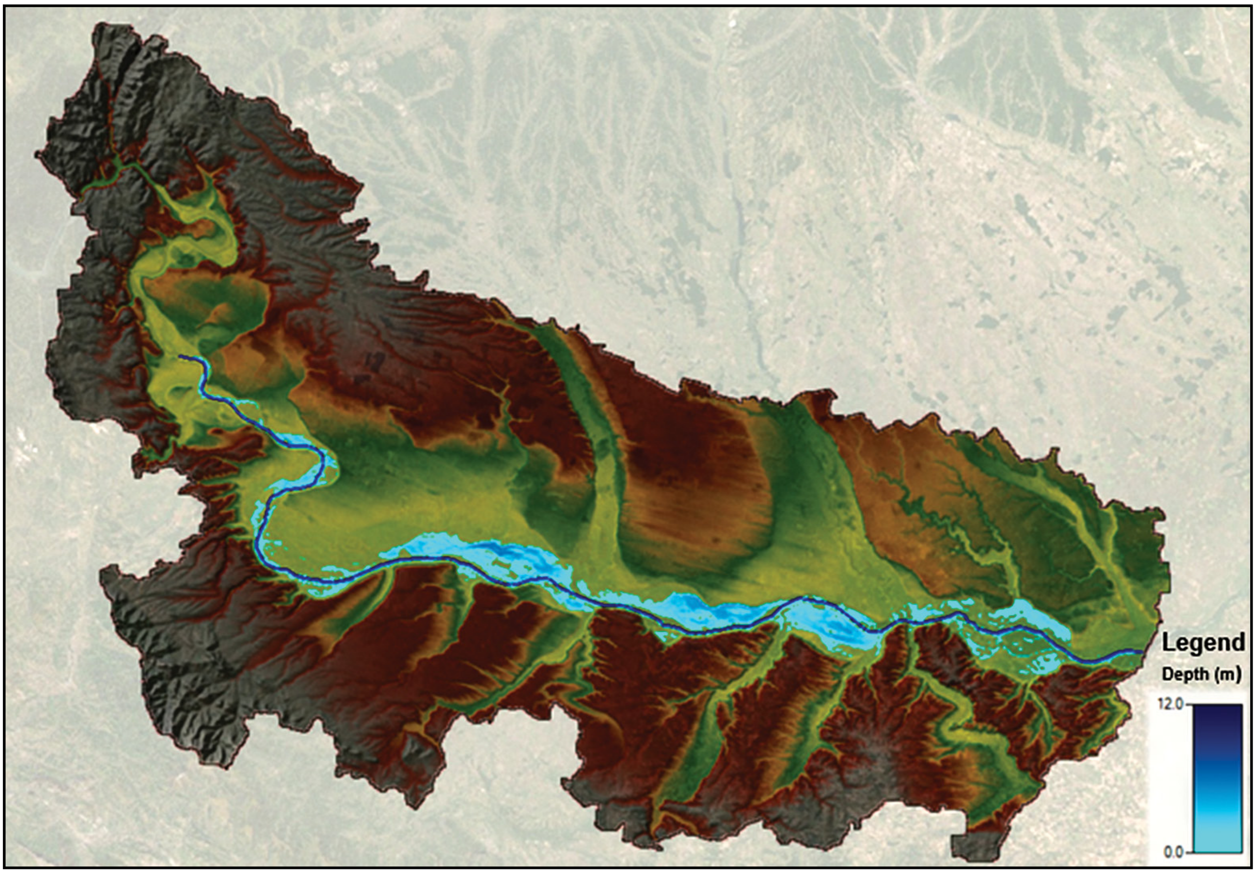
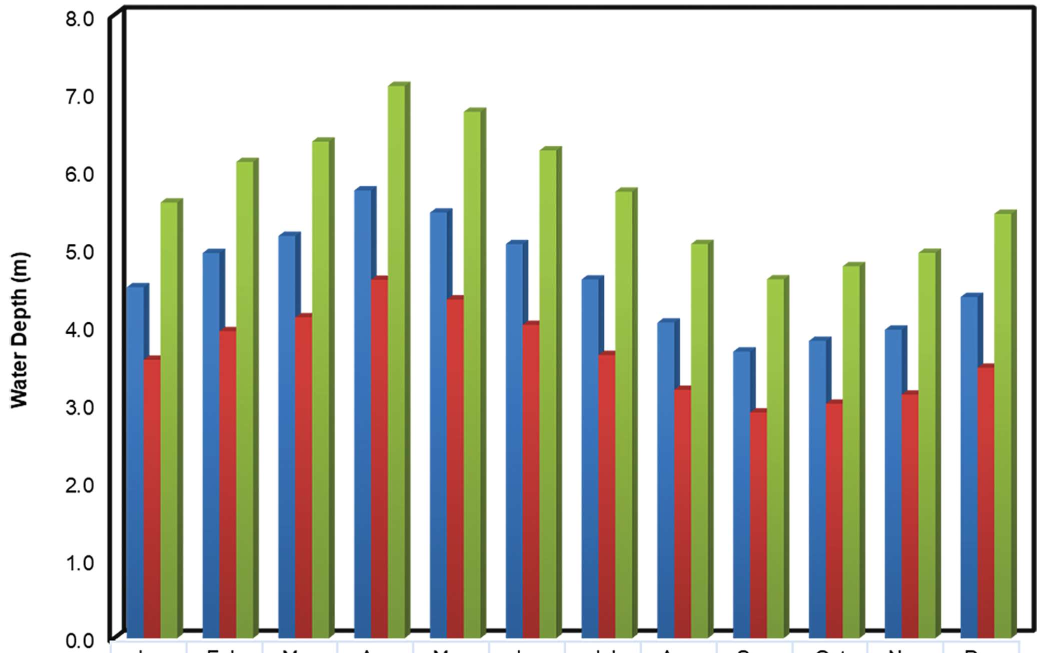
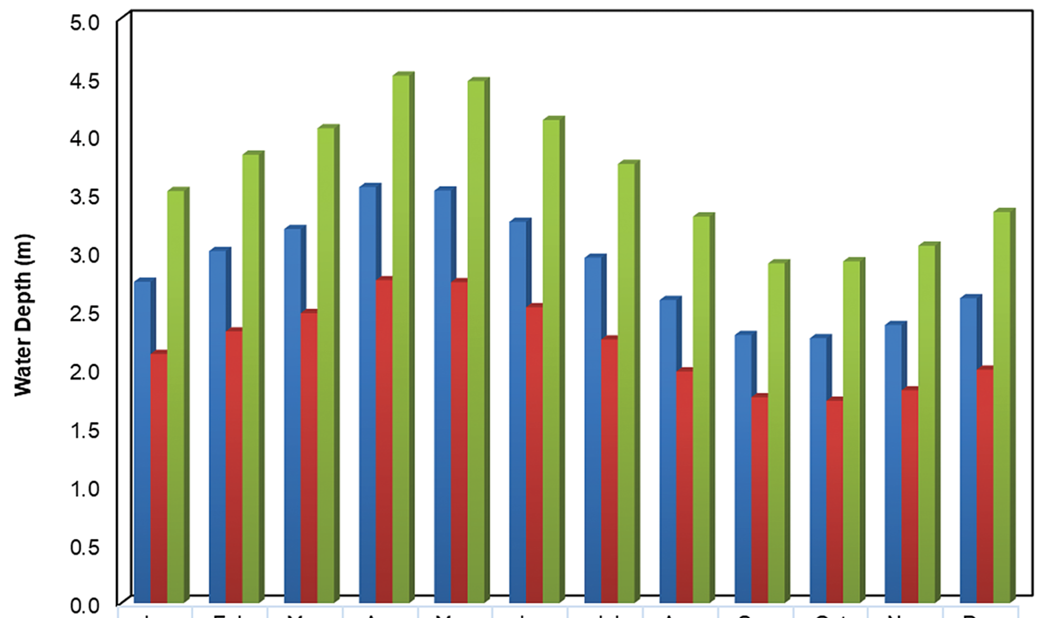


Fig. 19. Simulation of discharge under dry flow year.



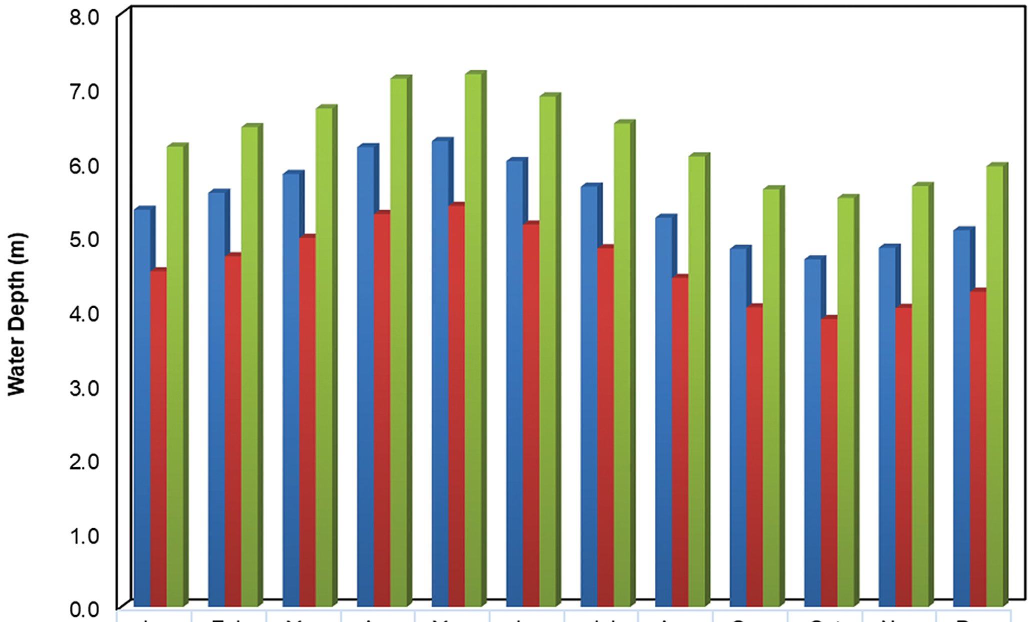
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Normal	4.5	4.9	5.2	5.7	5.5	5.1	4.6	4.1	3.7	3.8	4.0	4.4
Dry	3.6	3.9	4.1	4.6	4.3	4.0	3.6	3.2	2.9	3.0	3.1	3.5
Wet	5.6	6.1	6.4	7.1	6.8	6.3	5.7	5.1	4.6	4.8	4.9	5.4

Fig. 20. Water depths at the upstream cross-section in dry, normal and wet flow years.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Normal	2.7	3.0	3.2	3.6	3.5	3.3	3.0	2.6	2.3	2.3	2.4	2.6
Dry	2.1	2.3	2.5	2.8	2.7	2.5	2.3	2.0	1.8	1.7	1.8	2.0
Wet	3.5	3.8	4.1	4.5	4.5	4.1	3.8	3.3	2.9	2.9	3.1	3.3

Fig 21. Water depths at the mid-cross section in dry, normal and wet flow years.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Normal	5.4	5.6	5.8	6.2	6.3	6.0	5.7	5.2	4.8	4.7	4.8	5.1
Dry	4.5	4.7	5.0	5.3	5.4	5.2	4.8	4.4	4.0	3.9	4.0	4.3
Wet	6.2	6.5	6.7	7.1	7.2	6.9	6.5	6.1	5.6	5.5	5.7	5.9

Fig 22. Water depths at the downstream cross-section in dry, normal and wet flow years.

Following the water allocation model, a hydraulic model in HEC-RAS was built to determine the depth at predefined cross-sections of the major Danube river. The main findings of the study led to the conclusions below:

1. Given the fact that both reservoirs IG I and IG II operate as run-off-river systems, the greater the flow, the better the fulfilment of the demand, and vice versa. Spring months, particularly April, are associated with higher demand fulfilment, whereas September has the most unmet demand for energy production in the whole year.
2. Considering the specified crops and crop calendar, there is no unmet demand for agricultural production in the area in any of the described scenarios. The available water is far greater than the monthly and annual crop water demand. This was also perceived in the REXUS project document, which claimed that the problem is with irrigation infrastructure rather than water availability for agriculture.
3. Higher flows correspond to great depths, and vice versa. According to the stated fact, the water depth constantly drops over the summer and autumn months, causing difficulties in the smooth operation of navigation vessels. Navigation will be severely hampered in low flow conditions, where depths are substantially lower than in normal and wet year periods.

This study was conducted under various assumptions and limitations ranging from insufficient detailed observed data to high-resolution DEM for hydraulic modelling. In order to refine and improve the outcomes of such a study it would be recommended to acquire long-term detailed recorded data from relevant authorities; and investigate the land use/land cover effect on the water supply and demand gap in the research area.

The study showed the possibility to define a framework of analysis for the water-food-energy nexus in the study area, which can be the starting point of collaboration and negotiations for water use between different stakeholders in the area.

ACKNOWLEDGMENTS

In this research Sanaullah Salam and Albert Scrieciu were supported by the H2020 REXUS project (Grant Agreement No 101003632) and by the Core Program (Program Nucleu) contract no. 13N/08.02.2019, NIRD GeoEcoMar. We thank the two previous projects for data provision as well. Sanaullah Salam was also supported by the Grant number 2018-1514/001-001-EMJMD (Flood Risk Management) of the European Commission.

REFERENCES

Ali, S., Abraham, E., Sewilam, H. (2019). System dynamics modelling of the water, energy and agriculture nexus in Egypt. doi 10.13140/RG.2.2.14142.41289.

Adgolign, T.B., Rao, G.V.R.S., Abbulu, Y. (2015). WEAP modelling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. *Sustainable Water Resources Management* (2016), **2**: 55-70. doi 10.1007/s40899-015-0041-4.

Bene, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., and Williams, M. (2015). Feeding 9 billion by 2050 – putting fish back on the menu. *Food Security*, **7**(*2*): 261-274.

Comoglio, C. (2011). Scoping mission at Iron Gates I and II dams (Romania and Serbia) Preliminary assessment of the feasibility for providing free passage to migratory fish species – Report, by The food and agriculture organisation of the United Nations; available at http://awsassets.panda.org/. Last accessed on October 2022.

Cole, M.B., Augustin, M.A., Robertson, M.J., and Manners, J.M. (2018). The science of food security. npj *Science of Food*, **2**(*1*): 1-8.

Engineering Toolbox, (2004). Manning's Roughness Coefficients. Available at: https://www.engineeringtoolbox.com/mannings-roughness-d_799.html. Last accessed on October 2022.

European Environment Agency (EEA) (2018). Water use in Europe – Quantity and quality face challenges. Available at https://www.eea.europa.eu/signals/signals-2018-content-list/articles/water-use-in-europe-2014. Last accessed on October 2022.

FAO Rome (2017). The future of food and agriculture Trends and challenges. Food and Agriculture Organisation of the United Nations Rome.

Ferroukhi, R., Nagpal, D., Lopez-Pena, A., Hodges, T., Mohtar, R., Daher, B., Mohtar, S., and Keulertz, M. (2015). Renewable energy in the water, energy & food nexus. IRENA, Abu Dhabi.

Hoff, H. (2011). Understanding the Nexus, Background Paper for the Bonn, 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.

Mirdashtvan, M., Najafinejad, A., Malekian, A., Sadoddin, A. (2021). Sustainable Water Supply and Demand Management in Semi-Arid Regions: Optimizing Water Resources Allocation Based on RCPs Scenarios. Water Resources Management (2021) 35:5307-5324. doi.org/10.1007/s11269-021-03004-0.

Pagano, A., Portoghese, I., Giordano, R. (2022). Deliverable 4.1 – Report on PSM and SNA. Identification of DOs, NRQs and NIs. www.rexusproject.eu.

Postel, S., Vickers, A. (2014). State of the World 2004: Boosting water productivity. 21st Edition, Routledge, 2014. Available at https://www.taylorfrancis.com/chapters/edit/10.4324/9781315065694-14/boosting-water-productivity-sandra-postel-amy-vickers.

Roser, M., Ritchie, H., Ortiz-Ospina, E., Rodes-Guiro, L. (2013). World Population Growth. Published online at OurWorldInData.org. Available at https://ourworldindata.org/world-population-growth. Last accessed on October 2022.

Scholten, A., Rothstein, B., Navigation on the Danube - Limitations by low water levels and their impacts; EUR 28374 EN; doi:10.2788/236234.

Smith, M. (1992). CROPWAT – A computer program for irrigation planning and management, Irrigation and Drainage Pap. 46, Food and Agric. Org. of the U. N., Rome, 1992. Global runoff discharge center. Available at https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Stations.

The International Commission for the Protection of the Danube River (ICPDR) (2019). The Danube River Basin: Facts and Figures.

United States Department of Agriculture (USDA) Foreign Agriculture Service. https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx.

Viadonau (2019). Manual on Danube Navigation. Österreichische Wasserstraßen-Gesellschaft mbH, Donau-City-Strasse 1, 1220 Vienna, Austria. www.viadonau.org.