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IRRIGATION WATER USE IN THE DANUBE BASIN: FACTS, GOVERNANCE AND APPROACH TO SUSTAINABILITY

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Abstract

In this paper we assess the irrigation water use in the Danube Basin, highlight its complexity, identify future challenges and show the relevance for a basin-wide integrative irrigation management plan as part of a more holistic and coherent resource policy. In this sense, we base our integrative regional assessments of the water-food-energy nexus on insights from an extensive review and scientific synthesis of the Danube Basin and region, experimental field studies on irrigation and agricultural water consumption, current irrigation related policies and strategies in most of the Danube countries, and regulatory frameworks on resources at European Union level. We show that a basin-wide integrative approach to water use calls for the evaluation of resource use trade-offs, resonates with the need for transdisciplinary research in addressing nexus challenges and supports integrative resource management policies within which irrigation water use represents an inherent part. In this respect, we propose a transdisciplinary research framework on sustainable irrigation water use in the Danube Basin. The findings were summarized into four interconnected problem areas in the Danube Basin, which directly or indirectly relate to irrigation strategies and resource policies: prospective water scarcity and Danube water connectedness, agricultural droughts, present and future level of potential yields, and science based proactive decision-making.

Keywords: basin-wide irrigation management, resource policies, transdisciplinary research, Danube Basin

INTRODUCTION

Irrigation is by far the largest user of blue water regionally and worldwide (Foley et al., 2011; FAO, 2012). It represents an important technological measure in agricultural production to compensate for a shortage of rainfall during the growing season. This shortage can be structural and physiological whenever there is permanently not enough rainfall to produce yields and it can be temporal with irrigation used episodically for drought mitigation. Irrigation also represents an economic leverage point for farmers to increase yield in environments with natural water stress. These aspects and the fact that irrigation water leaves the system through the atmosphere and cannot be reused make irrigation central to sustainable water resources management. It also calls for widening the term irrigation management from the narrow technical understanding of the management of irrigation systems towards a river basin approach, which includes issues like optimized allocation of irrigation within a basin, balancing blue water demand and availability as well as upstream-downstream benefit sharing.

Considered from a systemic point of view, irrigation adds complexity to the water-food-energy nexus because irrigation converts comparatively large amounts of blue into green water, which links food production to regional blue water availability. The use of blue water also makes irrigation, and thereby food production, an upstream-downstream issue and creates the strongest spatial interdependencies of all water-food-energy nexus factors. Water connects different geographical regions and transfer valuable energy and water resources from upstream to downstream. As a consequence, water management cannot solely be local. In order to warrant sustainability and maximize welfare of all participants in a watershed, it should be explored ways to identify the most beneficial, efficient and equitable use of the common resource.

Furthermore, climate change directly influences irrigation regimes through changes in blue water demand and potential agricultural yields (Molden et al., 2010; Porter et al., 2014). Regional blue water availability might also significantly change, thereby putting pressure on the regional balance in the use of a basin's land and water resources (Rosenzweig et al., 2014; Iglesias and Garrote, 2015).

Irrigation plays a central role in achieving water, food (and more broadly land) and energy related Sustainable Development Goals (UN, 2015). They are not only strongly interlinked with each other but are also strongly connected with social and economic Sustainable Development Goals (Nilsson et al., 2016). There is no doubt that each goal is meaningful by itself in achieving sustainable development. Nevertheless, today the ways towards reaching them are not operationalized in terms of management and verification. The central scientific and operational challenge in achieving the Sustainable Development Goals until 2030 is how to align the pathways towards reaching each one of them in ways that amplify each other.

The above mentioned aspects are relevant particularly in the context of doubling global agricultural production until 2050, in order to satisfy the demand of a growing and wealthier world population (FAO, 2012). Agricultural production depends on climate and on natural resources of which, land and water are the most important. Rainfall, which hits the land surface is stored in the soils and thereby makes land and water interconnected and partly interchangeable. Access to more rainfall can be granted to agriculture by expanding the cropland area in non-cultivated places. Rainfall can also be used more efficiently on today's cropland through improved agricultural management practices. Finally, blue water can be added to the rainfall through irrigation to improve water availability to the crops. Since suitable cropland is limited and since most of it is already in use, expansion of cropland area is not considered feasible and sustainable to raise agricultural production (Zabel et al., 2014). This is supported by the need to protect natural habitats and biodiversity. The most promising way to satisfy future demands is to increase input efficiency in crop production.

Gains in water use efficiency (i.e. reducing the amount of water that is needed to produce a kilogram of yield) both in rain-fed and irrigated agriculture, therefore, represent the main pathway towards satisfying future food demands (Mueller et al., 2012; Brauman et al., 2013), including overcoming environmental and economic impacts of unsustainable water use.

Closing the gap between current agricultural production and future demand, therefore, calls for an intensification that is sustainable (Godfray and Garnett, 2014; Mauser et al., 2015). Since the level of intensification that is still sustainable is not easy to define and since this level can vary from field to field only rough estimates exist today on the gap between current yields and a possible sustainable increase in yield. This has been summarized for different countries by Bruinsma (2009) and is shown in Fig. 1.

Fig. 1 shows the difference between the actual (in blue) and the agro-ecologically attainable yield (in red) for wheat. Negative red columns mean that the actual yields are already above the ecologically attainable level, positive red columns mean that reserves exist for sustainable intensification. Three countries in Fig. 1 are part of the Danube Basin: Germany, Hungary and Romania. Whereas in Germany the current yield levels

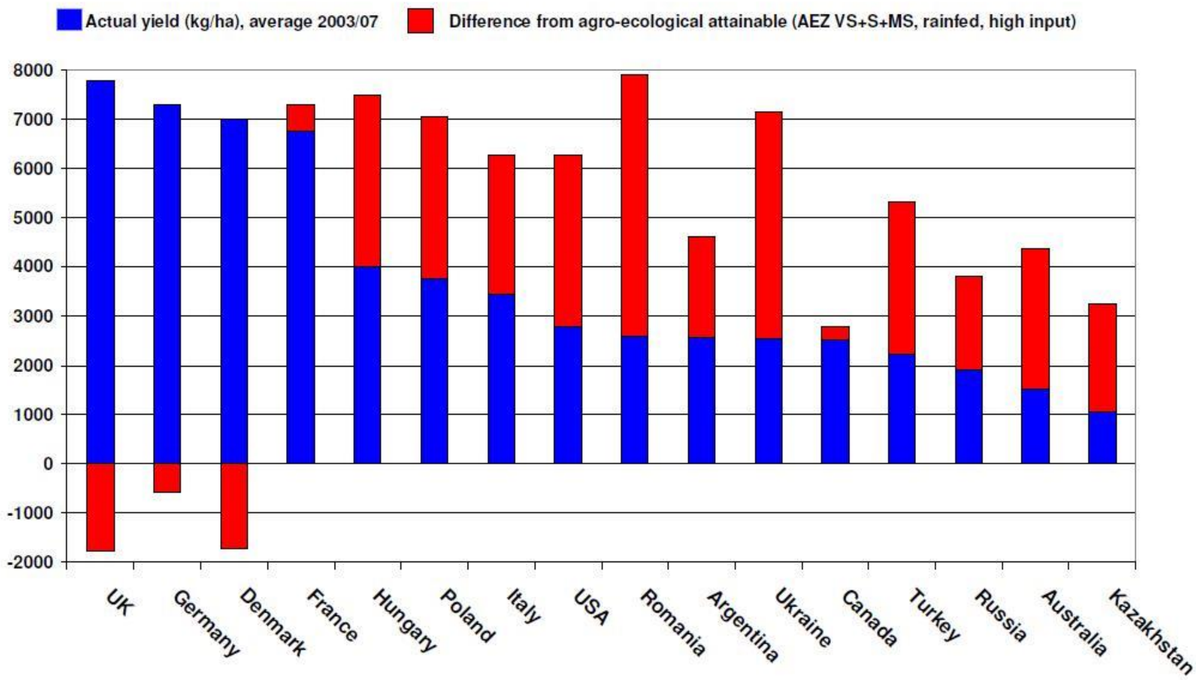

Fig. 1 Difference between actual and agro-ecologically attainable yield for wheat in selected countries, where VS stands for 'very suitable' land for crop production potential (i.e. the attainable yield is 80 to 100 percent of the maximum constrained-free yield); S is 'suitable' land (i.e. 60-80%); MS means 'moderately suitable' land (i.e. 40-60%) (from Bruinsma, 2009). The agro-ecological zone (AEZ) defines a standardized methodological framework for the characterization of climate, soil and terrain conditions relevant to agricultural production (Fisher et al., 2012, 2002)

are beyond the ecological limit, Hungary and Romania still hold reserves of 100% and more for sustainable intensification in rain-fed and irrigated agriculture. This makes it worthwhile to thoroughly examine the Danube Basin for hot-spots for land use change, intensification and increase in water use efficiency.

These aspects call for exploring and developing basin-wide, coordinated and adaptable management approaches which ensure the most beneficial, sustainable and equitable use of blue and green water resources, specifically for irrigation. Spatial and sectoral alignment of the water, food and (renewable) energy management is, therefore, the key for adaptive, sustainable and integrated irrigation schemes, which create both downstream and upstream welfare effects.

How does this translate to river basins within large political entities like the European Union? The EU constituted on the subsidiarity principle and the idea of solving each problem at the institutional scale at which it can be solved in the most appropriate and effective way. How does the idea of managing irrigation in the nexus sense relate to the subsidiarity principle in a situation when the administrative boundaries in a river basin are largely national or provincial and, therefore, do not coincide with the river basin or sub-basin boundaries? How could upstream-downstream benefit sharing from coordinated, basin-wide and adaptive irrigation management be envisioned in such a situation?

The scope of this article is thus to provide a scientific and policy documented source of information for a co-design research approach in which academia and stakeholders concur with plans for sustainable irrigation water use in view of integrative resource management in the Danube Basin.

STUDY AREA: THE DANUBE BASIN

We chose the Danube Basin to assess the current situation of irrigation and its potential future role as an exemplary case study to show the current knowns and unknowns on the way towards a coordinated, basin-wide and adaptive future irrigation management. The Danube Basin is the largest river basin in the EU (i.e. it covers 801 463 km^2 and hosts about 81 million inhabitants) and the world's most international river basin, being shared by 19 countries.

The diverse natural conditions throughout the Danube Basin impose different shares of croplands in the landscape (Fig. 2), favoring or limiting irrigation application decisions where necessary. As such, the relief characteristics in the Upper Danube Basin, till the Morava River, favor cropping activities in the plains and low hills of the Bavarian Depression in Germany and in the intra-mountain plain, on the long rounded hills and in the high piedmont plains at the bottom of the Alps of the Vienna Basin. In the Middle Danube Basin, specifically in the Pannonian Depression, the agricultural activities are favored by the presence of fertile soils covered by loess, particularly in the large Pannonian Plain in Hungary (i.e. the Middle Danube Plain) which extends in Romania, Serbia, Croatia and Slovakia as well (Loczy et al., 2012). In the Lower Danube Basin which extends in Romania and Bulgaria, one of the most extensive agricultural regions of high productivity potential is the Romanian Plain, including the Danube alluvial plain (52 600 km^2). It has large areas of fertile soils of Chernozem type and a high diversity of ecological conditions (e.g. tabular plains covered by loess, piedmont plains, terraces plains, low subsidence areas, Danube terraces which in the western part are covered by sand dunes, etc.) (Romanian Geography V, 2005). In Bulgaria, the relief of the Moesian Plain, including the Danube alluvial plain, turns from flat and hilly in the western part to hilly-plateau toward east. The region is crossed by valleys with high depth phreatic layers, rendering rather difficult conditions for irrigation (Stefanov, 2002).

Rainfall decreases from West to East, from about 700-900 mm to about 400-300 mm. This leads to structural deficits in rainwater availability for agriculture in the Pannonian and, even more markedly, in the

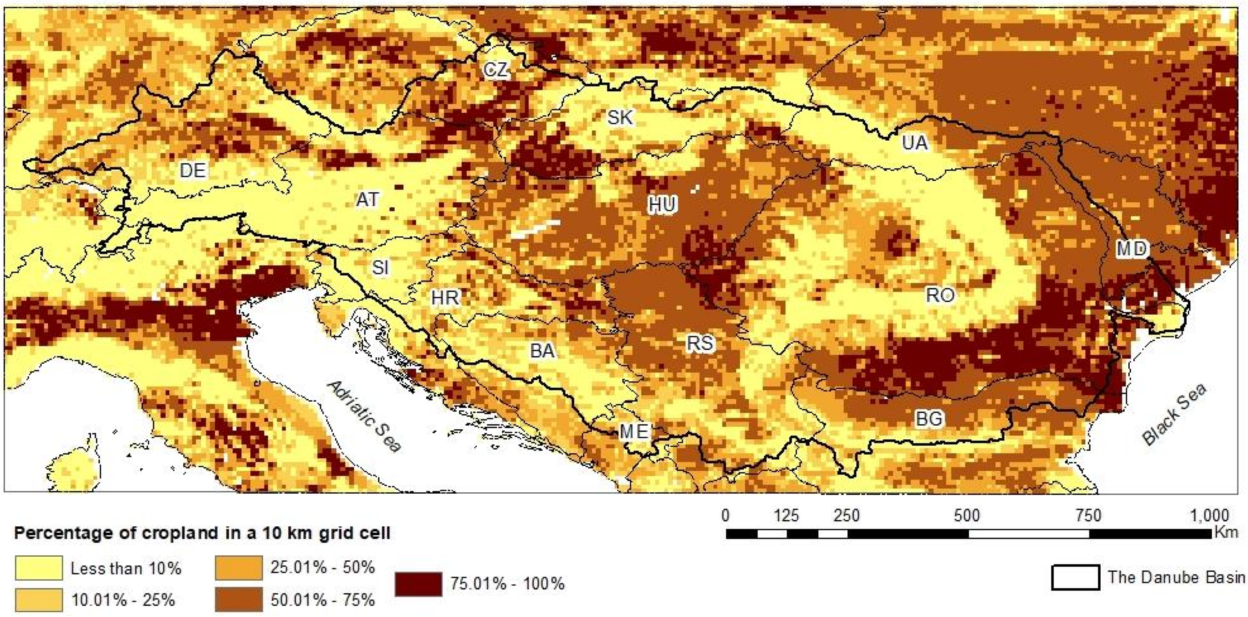

Fig. 2 Cropland in the Danube River Basin, (Dataset: Ramankutty et al., 2010)

Romanian plains. These large and fertile downstream areas of the Danube Basin can improve from irrigation to increase yields by reducing or mitigating water stress in summer and by increasing resilience against droughts, which will most likely be more frequent in a future climate. Large irrigation systems had been installed during communist times (i.e. 1960 – 1980s), proving the necessity for irrigation in these regions. They largely turned inoperative, particularly in Romania, during the transition period towards market economy (i.e. 1990s), while a possible relaunch would open up opportunities to establish new sustainable irrigation schemes in large parts of the basin. Governance schemes are in place on the EU (Framework Directives), the basin (International Commission for the Protection of the Danube River – ICPDR; Danube Strategy) and on the national, province and county level to manage the water, food, (renewable) energy and land resources. We assume that these multiscale governance schemes contain large untapped potentials for alignment and spatial interconnection.

Climate change is an important driving force that affects nexus resources and induces strong spatial differences within the Danube Basin (ICPDR, 2013; Mauser et al., 2018). Temperature increase, variation in rainfall amounts and their changing distribution patterns are expected to cause significant modifications in the hydrological regimes of the Danube sub-basins, resulting in more frequent periods of severe low flow conditions and decreasing summer discharges in the Upper Danube (Mauser and Hank, 2008; Mauser and Prasch, 2016) and more frequent, longer and intense drought periods in the Lower Danube (CLAVIER, 2009). Such impacts are likely to affect the water balance of the entire basin and the sub-basins and lead to increasing stress on the water resources, which further result in impacts on actual evapotranspiration and increase of irrigation water demand, while decrease the flow in rivers which are main sources for irrigation (Pistocchi et al., 2015; Bisselink et al., 2018). At the same time climate change and elevated CO_2 concentrations will strongly affect the agricultural yield potentials in the basin. On the one hand climate change will generally decrease water availability on the other hand however, increasing CO2 levels will improve water use efficiency for most agricultural crops. The net effects on yields can be very diverse regionally and the potentials are not known yet in detail. Most likely, the land use and irrigation regimes in the Danube Basin will be strongly influenced.

In view of the above-mentioned arguments, the Danube Basin is ideally suited for our study because it offers a complex web of (historical) regional needs for irrigation, climate gradients and climate change, multiscale institutional settings, different farming practices in the Danube countries, and different economic development dynamics.

IRRIGATION AND WATER-FOOD-ENERGY NEXUS IN THE DANUBE BASIN

Insights on irrigation sector in the Danube countries in relation to water-food-energy nexus were derived from profiled literature referring to topics such as: agricultural drought and management, water use efficiency, water scarcity, virtual water, and climate change implications on water resources. Furthermore, we documented the European Union's and national existing regulations, norms and future development plans with respect to water management, including irrigation water use. These aspects are described in the section below.

EU/Danube Basin interdisciplinary research projects

European Commission (EC) signals that water scarcity and drought have become growing challenges for many parts of Europe over the last decades, generating increasing costs and damages and potentially leading to changes in irrigation water regimes, particularly in the Lower Danube (EC, 2009, 2012; Pistocchi et al., 2015). Water scarcity, drought, desertification and climate change impacts and the associated risks in Europe, including Danube countries, have been assessed over the last decade in a number of EU interdisciplinary projects (e.g. CC-WARE, CLAVIER, SEE-RISK, RE-CARE, IMPACT2C, MACSUR, DROUGHT R & SPI) funded by EU-FP6, EU-FP7, ERDF or Cohesion Funds. Broadly, this research covers drought risk management topics, with a focus on impact assessments on cropping systems and farmers in most drought-affected regions of Europe (GWP CEE, 2015; MACSUR, 2017; Siebert et al., 2017), as well as on characteristic drought indices representation under current and climate change conditions (Blauhut et al., 2016).

The latest projects funded through the Interreg Danube Transnational Programmme (i.e. Interreg DTP, a funding instrument targeting the Danube Region in particular), e.g. DriDanube DTP, whose objective is the assessment of drought related risks in the Danube Basin, and CAMARO-D DTP, with a focus on the assessment of land use impacts on water regimes in the Danube River Basin, serve as examples of investigating optimum options of land and water integrative management through several case-studies.

Moreover, the growing signals of water scarcity, which is prospective in the case of the Danube Basin under climate change (Pistocchi et al., 2015; ICPDR, 2015; Bisselink et al., 2018), suggest a stronger emphasis on the international or regional trade of food and products in the context of virtual water (i.e. the green and blue water used in producing the commodity) concept. For example, the Danube Basin could shift from a net virtual water importer into a net exporter under particular dietary scenarios considering only the case of the agricultural products (Vanham and Bidoglio, 2014).

A number of European database structures (e. g. EURO-CORDEX and predecessors, CarpatClim, EC EUROSTAT and EC Joint Research Center portals) provide domain parameters such as climate variables and impact climatic indices, as well as comprehensive environmental and socio-economic indicators. Worth mentioning the FAO AQUASTAT dataset which offers statistics and gridded data at 5 minutes grid-cell resolution (about 10 x 10 km2 near the equator) on irrigated areas and areas equipped for irrigation (Döll and Siebert, 2000; FAO Aquastat, 2013). However, the need for accurate monitoring of irrigated areas in Europe with the support of the Global Monitoring for Environment and Security

Programme (GMES/COPERNICUS) and its fleet of remote sensing satellites is expressed by European Commission's aims towards achieving water use efficiency (EC, 2012).

Scientific information at regional and national level

The contextual literature on irrigation has been informing on the particularities of the irrigation sector in the Danube countries, particularly in the Lower Danube where irrigation has a long tradition. While the syntheses on irrigation remain valuable sources of information in terms of past developments of the agricultural infrastructure, crop suitability and environmental impacts in irrigated areas (Grumeza and Kleps, 2005; Bárek et al., 2009), the local case-studies provide details on the conditions and parameters of various agricultural regions for optimum irrigation schemes, such as timing, watering norms, water use efficiency in irrigated vs. rain-fed conditions, etc. The results of numerous empirical studies and field experiment applications concerning irrigation water use for most common crops under various local conditions in the Danube Basin are found in the annual series and communications published in the journals and bulletins of specialized institutions, such as the National Research Institute of Agriculture in Romania, the Agricultural Faculties (e.g. Scientific Papers. Series A. Agronomy, 2012 – 2017) or the Slovak Agricultural University (e.g. Acta horticulturae et regiotecturae).

However, only few landscape scale studies in the Danube Basin provide evidence on the influence of the changing climate conditions on water resources and agricultural productivity, and in the context of increasing demands for food, water and bioenergy. For instance, GLOWA-Danube project represents an example of integrative assessment of the regional effects of climate change in the Upper Danube. It is based on an integrative decision support system (i.e. DANUBIA) consisting of various natural based and social science based sub models which allow the design and assessment of complex scenarios for future development, envisaging impacts on water resources (Mauser and Prasch 2016). Likewise, the ICPDR case study on Tisza River Basin, in the Middle Danube region, stresses the importance of integrated management of water and land resources due to the impacts of agriculture resulted from water abstractions and nitrate pollution (ICPDR 2012). Moreover, the ICPDR Report (2017) on the 2015 drought points out that agriculture was by far the most affected sector and in areas with periodical irrigation, such as the Marchfeld in Austria, water demand was significantly above the long-term average. The Report concluded that water scarcity is likely to increase in the Danube Basin, drought will be one of the future priorities in water management, better data monitoring for agricultural water withdrawals and, enhanced dialogue between the water and the agricultural stakeholders are needed.

EU/Danube Basin regulatory frameworks

The regulatory framework for the Danube Basin management has been constantly developed since the Danube River Protection Convention was signed in 1994 in Sofia (BG) by the riparian countries. Focusing in the beginning on the quality of the water and environmental protection, it evolved, up to present, toward the integrative management framework of ICPDR. The latest river basins management plans in the Danube Basin represent a common effort of the Danube countries to work on and respond to integrated land and water management requirements, considering future water demands and climatic conditions (ICPDR, 2015).

The Water Framework Directive (WFD) in particular targets long term actions such as protection of waters so as to achieve a qualitatively and quantitatively good status of all waters in Europe, including efficiency of water use, adequacy of agricultural practices and coordinated water-pricing policies. Likewise, certain EU's Common Agricultural Policy (CAP) subsidies are contingent on meeting the objectives in WFD through Cross Compliance and agri-environmental measures with the purpose of decreasing the agricultural pressures caused by water abstractions and hydromorphological changes, thus enhancing the synergies between water and agricultural policies (EEA, 2012). At the same time, CAP aims at ensuring food security, climate adaptation, a competitive and dynamic farming sector and green economy by supporting the economic growth while preventing environmental risks (EC, 2010). It is acknowledged that sustainable agricultural measures can support water management through sustainable farming practices. More efficient water saving irrigation techniques will have to be developed and applied along with sustainable regulatory actions envisioning water use with special attention to water demand to prevent or effectively respond to water scarcity challenges (ICPDR, 2015).

Although the principles of the European water and land use policies are meaningful, their implementation throughout all member states (including Danube countries) is a complex and difficult process. It relates to integrative management of resources and active transboundary cooperation in the context of sharing resources among countries. Such aspects are not straightforward, but marked by complex trade-offs among sectors or risks induced by market mechanisms which usually are oriented towards achieving greater profits, or by regional particularities (e.g. economic evolution pathways, cultural legacy, governance structures, etc.) which may make particular legislation problematic for one country but suitable for another. Nevertheless, achieving cross-sectoral and cross-scale cooperation for an integrative and sustainable resource management is dependent on the political will, stakeholder commitment and working institutional arrangements to manage resource nexus issues (Hoff, 2011; Allouche et al., 2015).

National regulations and development strategies for irrigation in the Danube Basin countries

This section synthesizes the main aspects regarding irrigation management and irrigation future development plans in the Danube countries where irrigation has been playing an important role for agriculture and represents central issue for climate change adaptation and mitigation strategies (Table 1).

Table 1 Schematic information on irrigation regulatory designs and perspectives in the Danube basin' s countries

Country	Current situation (brief note)	Regulatory instruments for irrigation	Development perspectives
Germany	DE is relatively rich in water resources. Recent experience in irrigation due to increasing drought spells.	Permits are needed to allow for the abstraction of an allotted volume of water for irrigation (Germany´s Federal Water Act).	No specific development plans for the German part of the Danube (i.e. Baden-Württemberg and Bavaria). However, the federal states make use of the subsidizing options to a very varied degree (Bosch & Partner GmbH, 2014).
Czech Republic	The actual use of the irrigation systems accounts for about 25-30% of the area equipped with irrigation which is of 160 000 ha, i.e. 3.65% of agricultural land (Trnka et al., 2016).	Irrigation water is used on the basis of permits for water abstraction; payments are applied for abstractions larger than 6 000 m^3/year or 500 m^3/month.	The rehabilitation of the existing infrastructure and development of new systems are envisaged in view of future increased areas affected by precipitation deficits due to climate change (Trnka et al., 2016).
Slovakia	Initially covering 321 000 ha (~20% of arable land), the operational systems nowadays can cover 72 565 ha (Hydromeliorácie, š.p. Report, 2016).	The Ministry of the Environment has introduced a fee with the lowest possible impact for irrigation water consumption (Act no. 303/2016).	An increase of the irrigated area to 892 000 ha, or at minimum to 700 000 ha, is required in order to prevent climate change effects (Koncepcia, 2014).
Hungary	Water sources are based on transient waters. During 2009 – 2011 about 70 000 ha were irrigated and in 2015, 128 328 ha (i.e. 2.4% of the agricultural area) (EC, 2015).	Permits for irrigation are issued by the General Directorate of Water Management / subordinated institutions on the basis of contracts for irrigated areas.	To minimize the effects of drought, it is expected that the irrigation area could increase to about 180 000 ha, although there is a great uncertainty about the required water quantities abstracted for irrigation (ICPDR, 2012).
Republic of Serbia	Transient waters are sources for water abstraction for irrigation; the irrigation systems cover a relatively small area of cultivated land (i.e. 105 000 ha out of 2 016 716 ha of arable land) (MAEP, 2015a).	Water permits are issued for land owners or suppliers of irrigation water for a certain amount of abstracted water. Farmers pay half of the tariffs set out for the irrigation.	The irrigation area is going to increase to 350 000 ha by the end of 2030 through rehabilitation of the existing systems and construction of new infrastructures, along with nonstructural measures (e.g. knowledge transfer, consultancy for farmers, etc.) (MAEP, 2015a).
Romania	It benefits from a large experience in irrigation. During 70s-80s, an extensive irrigation system was installed, i.e. ~ 3 million ha out of 9 389 200 ha (INS, 2015). In the recent past (2009 - 2016) about 600 000 ha totals the land that could be irrigated (AFIR, 2017).	A yearly subscription for an allotted volume of irrigation water was available until recent to farmers (Law no. 138/ 2004, amended by Law no. 158/ 2016). Presently, the costs for irrigation water (i.e. the costs of water and energy for pumping) are totally subsidized (Law no. 133 / 2017).	The National Programme for the Rehabilitation of the Primary Irrigation Infrastructure of the Ministry of Agriculture and Rural Development (MADR, 2016) stipulates that 2 006 941 ha are going to be suitable for irrigation by 2020.
Bulgaria	Built during the 60s – 70s to cover about 740 000 ha (Velikov, 2013), the irrigation systems serve today only between 4% and 8% of the irrigable area, i.e. 541 779 ha (Ministry of Agriculture and Food, 2017).	Permits to abstract an allotted volume of water for irrigation issued according to the Water Act's conditions for water availability and sustainable use. The price for the irrigation water delivery service is determined annually by the Minister of Agriculture and Food (Decree No 16/20.01.2017).	The Strategy for the management and development of the hydraulic network and protection from harmful effects of water aims to increase the actual irrigated area by 2030 to 316 580 ha (Ministry of Agriculture and Food, 2016).

DISCUSSION ON THE CHALLENGES TO IRRIGATION WATER USE IN THE DANUBE BASIN

Irrigation in the reported data on water use

Reported data, where available, on water use in the Danube countries were analyzed in order to get an overview on the level of water demands in the basin, as well as on the possible gaps in data monitoring for sustainable irrigation management.

The shares of surface water abstractions from the Danube River Basin relative to the total surface water abstractions in each country highlight those countries dependent on Danube's water resources given their largest extent in the basin, i.e. Hungary, Romania, Slovak Republic, Serbia (Table 2). However, Danube Basin's surface waters are used according to each country's level of water resource availability, demand and supply endowment facility, ultimately depending on the environmental conditions and the socioeconomic development of the country.

Table 2 Volumes of fresh surface water abstraction from the Danube River Basin by country, total and by sectors, in million m^3, and as percentage of the country's total fresh surface water abstraction, in brackets. The percentages in the square brackets represent the fresh surface water abstraction from the Danube River Basin relative to the renewable freshwater resources existing in the respective country.

Danube country	**Total gross abstraction**	**Public water supply**	**Irrigation**	**Production of electricity (cooling)**
DE	3 181.70 (11.71%) [6.92%]	59.07 (3.90%)	-	-
CZ	194.54 (13.16%) [6.45%]	35.30 (10.54%)	12.25 (59.96%)	76.06 (11.93%)
SK	283.97 (99.12%) [0.35%]	46.38 (95.26%)	12.08 (100.0%)	-
HU	4 956.20 (100.0%) [4.28%]	255.20 (100.0%)	109.29 (106.1%)	3 862.43 (96.13%)
RS	1 288.87 (36.31%) [0.74%]	97.35 (48.26%)	40.20 (56.04%)	1 086.25 (34.54%)
RO	5 860.46 (100.0%) [15.03%]	606.14 (100.0%)	352.70 (100.0%)	1 050.11 (100.0%)
BG	2 931.05 (54.60%) [2.83%]	293.53 (60.11%)	20.42 (7.05%)	2 522.96 (73.18%)

Source of data: EUROSTAT, http://ec.europa.eu/eurostat/data/database; the data for most of the countries are averaged around the year 2011. The countries were considered based irrigation application relevance for the respective country (see Table 1) and on data availability, e.g. no EUROSTAT data for fresh surface water abstraction were available for Austria.

Romania stands out as the largest consumer of fresh surface water for irrigation among the Danube countries, considering only the Danube River Basin resources. However, this aspect is not reflected by the yield levels (e.g. in Romania maize achieves a yield of 4 t/ha as compared to 7.4 t/ha in HU; EUROSTAT, 2017). This is related to inefficient irrigation water use due to aspects such as low technical capacity of the exiting irrigation infrastructure, lack of cooperation between the water suppliers and farmers resulting in improper timing and norms of irrigation application, etc. (MADR, 2011). In essence, the extensive irrigation systems are characteristic for the large agricultural areas in the Middle and Lower Danube Basin, e.g. Hungary and Romania, where the infrastructure has been planned for large scale irrigation application. The climatic scenarios studies show increasing intensity and frequency of droughts particularly for Central and Eastern Europe (CLAVIER, 2009), thus requiring a careful allocation of water resources specifically in this part of the basin.

The data shown in Table 2 gives a first overview on the currently available knowledge on the diversity of irrigation in the Danube River Basin. It conveys two clear and important messages: 1) although all countries extract irrigation water from the common Danube water resources, data is largely available only on the national level, no comprehensive and homogeneous data set is available on the irrigation in the Danube Basin, 2) the reported data is strictly based on registered values of water that is metered for irrigation. It contains no information on how much of this irrigation water is productively used for the purpose to increase yields. From a water-food nexus perspective this aspect is bound to create confusion on how much water is actually consumed by irrigation at a certain location and on how much of the extracted water, which is metered, can in principle be used further downstream because it is not leaving the system.

Fig. 3 shows the irrigation water pathway from a resource nexus point of view. Water for irrigation must be extracted from a river or a groundwater aquifer and is

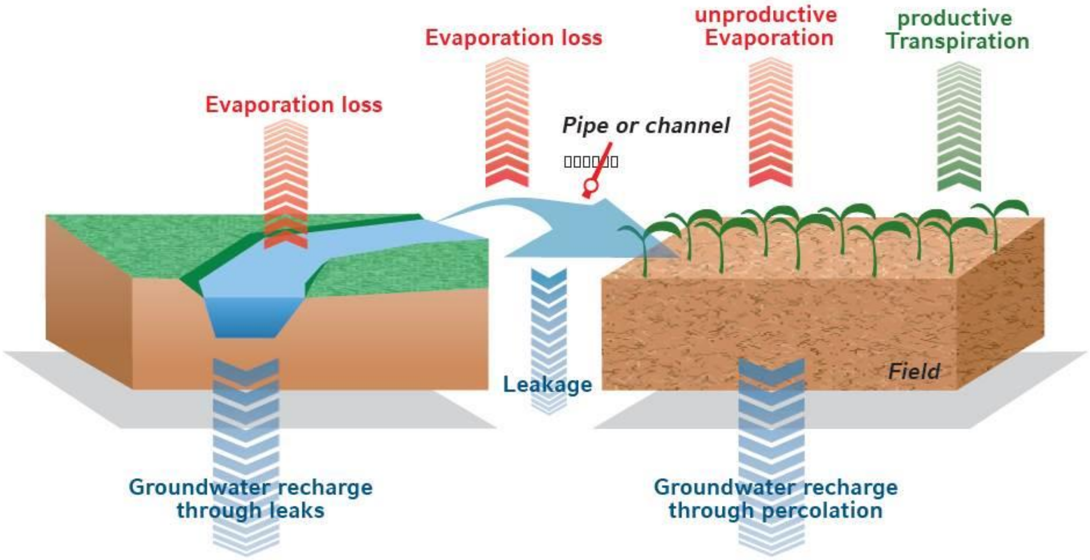

Fig. 3 Irrigation water pathway in the context of resource nexus

usually transferred to the point of use through open canals. The losses occur in the form of evaporation from the open water surfaces and leaks from the canals. These two losses are distinctly different from a nexus point of view. Whereas the water that leaks from the canals stays in the watershed and can in principle be harvested from the groundwater at a downstream location and is therefore not lost to the system, the evaporated water from the open waterbodies leaves the basin as part of the atmospheric circulation and is therefore lost for any alternative use in the basin. The water that is transported on the irrigated fields is metered and serves the basis for the statistics. On the fields, again, access water leaks to the groundwater and stays in the system, whereas (unproductive) evaporation from the ground and wetted leaves exits the system without effect on plant growth. Only the water that transpires through the plants, although it is lost to the system, has the desired irrigation effect to support plant growth. Inefficient irrigation water use therefore has two aspects: 1) the unproductive evaporation of water, which leaves the system, 2) the unproductive leakage of irrigation water into the groundwater; here the water stays in the system. Clearly from a water-food nexus point of view both pathways have to be minimized. Nevertheless, there is a fundamental difference between the two pathways, both in the consequences to the system and in the measures necessary to minimize the pathways. This is particularly important when water use issues involve shared waters. Therefore, the first pathway (i.e. unproductive evaporation) unnecessarily destroys water resources upstream and deprives the downstream users of water resources that would in principle be available. The second pathway (i.e. unproductive leakage) usually diverts water from surface to groundwater storage and leaves opportunities open for the downstream users. Unfortunately, these pathways are not reflected in the metered irrigation water use. This prevents a regulatory and governance framework which can adequately balance water availability and allocation of water to irrigation upstream and downstream and among different countries.

Framing a transdisciplinary research in the support of a basin-wide irrigation management plan

The tendency in the irrigation sector in the Danube countries is to increase the irrigated area and to offer legislative and financial support for encouraging the use of the already existing irrigation infrastructure and for the development of new systems. In Romania, for instance, increasing the irrigated area from about 0.5 million ha that can be irrigated today to almost 2 million ha by 2020 is an ambitious objective which aims to boost agricultural activities and production, contributing also to climate change adaptation and rural communities' resilience. In Bavaria, although it is not allotted a certain area for irrigation, the expected increase in water withdrawals for irrigation in the context of climate change is already an issue on the decision makers' agenda. Under these circumstances, central questions have to be addressed:

- If all Middle and Lower Danube countries implement their plans to expand irrigation, can water availability sustainably meet the created demands?
- Where in the upstream-downstream context will hot spots of water shortage be created?
- What will be the impact of climate change in altering the availability-demand relation in the Danube Basin?
- What role must advance irrigation monitoring systems, which are able to distinguish inefficient irrigation water pathways, and advanced irrigation technologies play to ensure sustainable irrigation and upstream-downstream benefit sharing?
- What governance concepts, including irrigation water pricing strategies, are effective and efficient in reaching the goal of maximizing the societal benefit of irrigation water for the whole Danube Basin?

Moreover, the paper highlighted a series of issues related to irrigation in the Danube Basin, such as: no basin-wide irrigation assessment is available for the Danube; the statistics express the irrigation water that is metered and not the water that is actually consumed to produce food; the EU legislation with respect to water and land resources, although profoundly integrative in character, is still difficult to be implemented in all Danube countries, raising complex resource trade-offs issues; irrigated agriculture in the Danube countries is significantly subsidized, fact that might further enlarge the economic and development disparities in the Danube Basin, although such measures are welcome by farmers; and, climate change impacts on irrigation are only known with a large degree of uncertainty.

Increased irrigation, profitable agriculture and climate change are common issues for all Danube countries. In this context, the question how Danube countries can solve irrigation and drought problems in a sustainable way is a transdisciplinary research endeavor as much as it is a cooperation and governance challenge, dealing particularly with the synergies and trade-offs of water for agriculture, hydropower, navigation and domestic use. To this end, the implications of water abstraction for irrigation in the Upper Danube countries on the availability of water resources for the downstream countries represent a research question that holds multiple cross-sectoral consequences (Mauser, 2017). This is connected to the topic of changing virtual water flows within the Danube Basin, being subject to scenario assessment in order to identify the optimal economic and social resolutions for all Danube countries (Vanham and Bidoglio, 2014). Collaborative efforts between academia and various stakeholders at different level in co-designing this type of knowledge is part of a solution-oriented research which goes beyond complex models, systemic and interdisciplinary problems to englobe in the research process developmental objectives, norms and visions which altogether aim at producing legitimate knowledge and guidance for intervention strategies (Mauser et al., 2013).

Considering the above-mentioned considerations on irrigation in the Danube Basin, we identified 6 interconnected themes for evaluating irrigation water use at a basin scale which could form an integrated research framework (Fig. 4). These are summarized below.

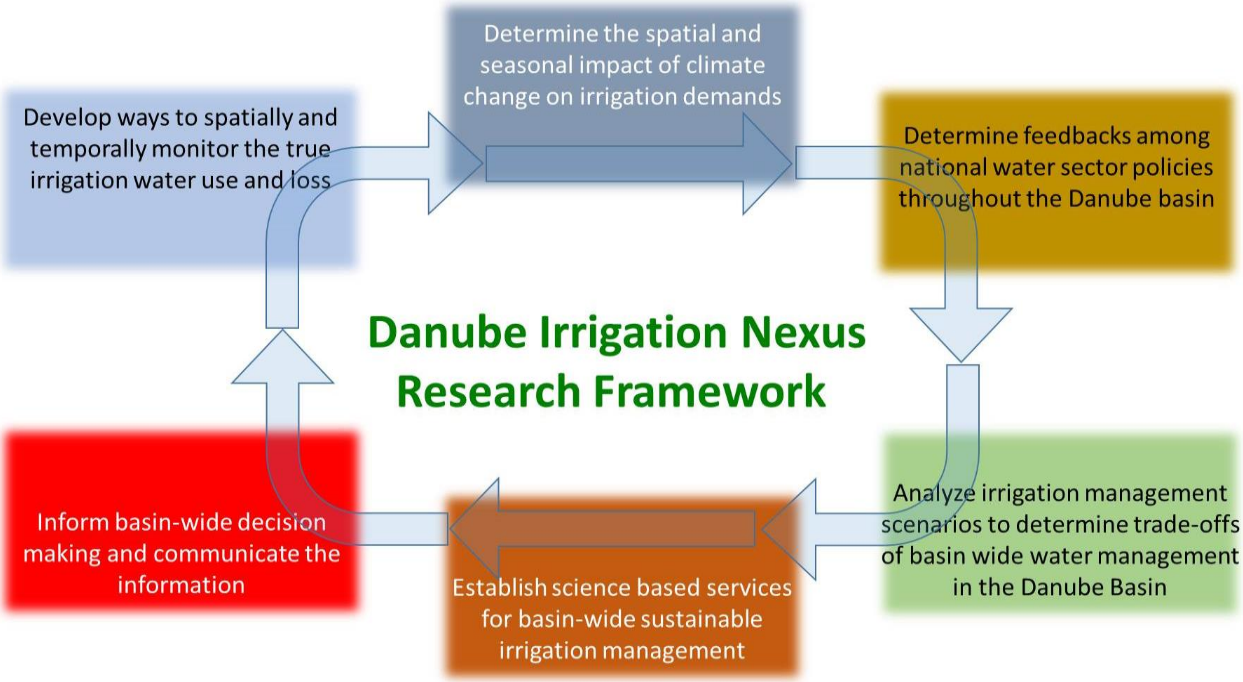

Fig. 4 Outline of the „Danube Irrigation Nexus Research Framework" for co-producing scientific knowledge for a basin-wide sustainable irrigation management plan

1) a basin-wide monitoring system that reflects the amount of irrigation water that is actually consumed by the cultivated crops as well as the additional amount of water needed to combat soil moisture deficits. The novel, basin-wide monitoring system can roughly be based on a combination of crop growth modeling and remote sensing time series taken from the available COPERNICUS satellites, in which the observed growth patterns on irrigated and non-irrigated fields are compared with simulations of plant growth and yield, from which real irrigation water consumption is determined by considering available rainfall;
2) climate change impact assessments on Danube Basin water resources highlighting potential regional hotspots of water shortages and its consequences for irrigation. This part is based on extensive basin-wide simulations of crop growth under current climate and future climate scenarios including CO_2 fertilization effects and determines the spatiotemporal distribution additional irrigation water demand;
3) the co-design (with relevant stakeholders) of scenarios of future development alternatives and their simulation in order to explore, in a transparent way, feedbacks (positive and negative) among national water policies / management decisions in agriculture (including irrigation), energy, industry, public use and ecosystem protection, with a special emphasis on exploring the mechanisms of upstream-downstream benefit sharing;
4) based on the scenario analysis, the trade-offs of decision alternatives are identified for sustainable water uses based on an active cooperation between stakeholders at different governance levels and academia;
5) derivation of science-based services for basin-wide irrigation management;
6) dissemination of scientific outcomes for informed decision-making at national and regional levels.

The above "Danube Irrigation Nexus Research Framework" relies on sophisticated new monitoring and simulation tools using the available COPERNICUS satellite data streams and smart environmental models. Nevertheless, at its core is the co-creation of knowledge on sustainable basin-wide irrigation water management, which is based on an intensive stakeholder cooperation process, which ensures that the practical benefits of a basin-wide nexus approach become transparent to the decision makers and the knowledge is created with the applicability of the results in mind.

CONCLUSIONS

The results of our regulatory mapping and literature review exercise for irrigation water use in the Danube Basin shed light on what is known on irrigation and its future in the basin. It shows the contributions of EU regulations, strategic plans and visions to resource management, including climate change effects on water resources, and the characteristics and conditions of the national regulatory frameworks related to irrigation application in the Danube countries. The challenges of the irrigation sector in the context of future developments and the implications for water-food-energy nexus are derived, ultimately leading to a proposed transdisciplinary research framework supporting a basin-wide irrigation management plan.

The scientific interdisciplinary projects form a rich heritage of data and conceptual and analytical outcomes proving substantial scientific support to base European resource policies and/or aid countries enabling regulation change towards resource sustainability. However, many of them deal with the impacts on resources by sub-systems (e.g. drought and agriculture, water and land use, or energy and water), being difficult to trace the entire chain of synergies and trade-offs within water-food-energy nexus due to the complex interlinkages between the resources. The research projects do not explicitly approach the issue of irrigation in the Danube basin by considering basin's water availability and resources nexus issues and the trade-offs among them.

Instruments such as allocation of important national and European structural funds for the rehabilitation of the existing infrastructures, governance and institutional (re)arrangements to ensure irrigation management and support of investments in on-farm irrigation systems were implemented. This is specific for Romania, a Lower Danube country with large irrigation application potential and need. In the Upper Danube, irrigation increased particularly as a response to changing climatic conditions. According to the future irrigation development plans, the irrigated areas are expected to increase throughout the Danube countries, the largest areas being located in the Middle and Lower Danube, affecting, therefore, the water balance of the entire Danube Basin.

The scientific information reflects several key points, highlighting the need for increased trans-national understanding of irrigation issues and implications for water resources management at Danube Basin level. Foremost, there is growing evidence that Central and Eastern Europe, particularly Lower Danube, is increasingly affected by droughts which under current development trajectories and climate change impacts will inevitably lead to *water scarcity problems*. Water scarcity, which means using more water than naturally renewable, is a driving force of long-term economic damages (ICPDR, 2015). Moreover, the impact of agricultural drought (i.e. insufficient soil moisture) on *crop yields losses* is not sufficient investigated to support agricultural sustainable practices, climate change adaptation and integrated resources management. Heavy precipitation events and impacts on yield losses and soil are also priorities in some Danube agricultural areas. At the same time, large agricultural areas in the Danube Basin (e.g. Romania, Hungary) benefit from arable land whose *production potentials* need to be accurately quantified to be sustainably exploited in view of both future climatic conditions and socioeconomic development pathways. *Integrative outcomes* regarding water consumption and agricultural production and active collaborations between academia and stakeholders for a better *use of the available scientific knowledge for proactive decision-making* need to be fostered. At present, the proactive measures meant for long-term sustainable development (e.g. enhancing the resilience of the agroecosystems to climatic extreme events) are less envisioned, lagging behind the reactive actions that are taken at times of crises (e.g. compensations for agricultural losses due to drought) (GWP CEE, 2015).

At the same time, water pricing could play a significant role for the improvement of irrigation water use. The potential physical scarcity of water (e.g. supply is affected by more variability and uncertainty due to climate change), its connectedness nature and its common pool resource character might interfere with efficient resource allocation and lead to market failures (Livingston, 1995), e.g. neglecting environmental impacts or underpricing of the resource (Johansson et al., 2002). Therefore, institutional arrangements have to be set up in order to achieve efficient water use, which means, in an economic sense, to equate the marginal benefits to the costs of the last unit of water used (Johansson et al., 2002). Supporting efficiency requires policy instruments that foster security and flexibility with regard to water rights and that consider the natural interdependency of water users (Livingston, 1995).

In this context, the development of a basin-wide irrigation management plan is a way forward to increasing water use efficiency and to sustainable development at large. Therefore, this paper outlines a research framework that advocates transdisciplinary studies, entailing integrative results on Danube Basin's water-food-energy nexus in which irrigation plays a central role, and where water resources governance could be realized by accounting for the spatial interconnectedness and equitable use of shared resources, aspects that are embedded in the European resource policies and strategies as well as UN Sustainable Development Goals.

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References

Allouche, J., Middleton, C., Gyawali, D. 2015. Technical veil, hidden politics: interrogating the power linkages behind the nexus. *Water Alternatives* 8 (1), 610–626.

ANIF – National Agency for Land Reclamation, 2017. Areas irrigated in the recent past. https://www.afir.info/ (accessed 12 March 2019).

Bárek V., Halaj P., Igaz D. 2009. The Influence of Climate Change on Water Demands for Irrigation of Special Plants and Vegetables in Slovakia, in: Střelcová K. et al. (eds.), Bioclimatology and Natural Hazards, Springer, 271–282.

Bisselink, B., de Roo, A., Bernhard, J., Gelati, E. 2018. Future projections of water scarcity in the Danube River Basin due to land use, water demand and climate change. *Journal of Environmental Geography* 11 (3–4), 25–36. DOI: 10.2478/jengeo-2018-0010

Blauhut, V., Stahl, K., Stagge, J.H., Tallaksen, L.M., De Stefano, L., Vogt, J. 2016. Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors. *Hydrology and Earth System Sciences* 20, 2779–2800.

Brauman, A.K., Siebert, S., Foley, J.A. 2013. Improvements in crop water productivity increase water sustainability and food security – a global analysis. *Environ. Res. Lett*. 8, 024030. DOI: 10.1088/1748-9326/8/2/024030

Bruinsma, J. 2009. The Resource Outlook to 2050: By How Much Do Land, Water and Crop Yields Need to Increase by 2050?, in Technical papers from the Expert Meeting on How to Feed the World in 2050 The Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/tempref/docrep/fao/012/ak971e/ak971e00.pdf (accessed 13 March 2019).

CLAVIER, 2009. Some general considerations of regional climate modelling in Eastern Europe, Results of WP1, http://www.clavier-eu.org/ (accessed 10 March 2019).

Döll, P., Siebert, S. 2000. A digital global map of irrigated areas. *ICID Journal* 49, 55–66.

Decree No 16/20.01.2017, Methodology for determining the service "delivery of irrigation water" in Bulgaria (CMD N 16/20.01.2017) http://www.mzh.government.bg/MZH/Libraries/ (accessed 23 January 2019).

EEA – European Environmental Agency, 2012. Water Resources in Europe in the context of vulnerability, http://europedirect.pde.gov.gr/images/pubs/Water-resources-in-Europe-in-the-context-of-vulnerability.pdf (accessed 2 April 2019).

EC – European Commission, 2009. White Paper. Adapting to climate change: Towards a European framework for action. https://ec.europa.eu/health/archive/ph_threats/climate/docs/com_2009_147_en.pdf (accessed 10 March 2019).

EC – European Commission, 2010. The CAP towards 2020: Meeting the food, natural resources and territorial challenges of the future. Available at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52010DC0672&from=EN (accessed 2 April 2019).

EC – European Commission, 2012. Blueprint to Safeguard Europe's Water Resources, Brussels. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012DC0673&from=EN (accessed 10 March 2019).

EUROSTAT, 2017. http://ec.europa.eu/eurostat/data/database (accessed 23 March 2019).

FAO, 2012. World agriculture towards 2030/2050: the 2012 revision, ESA Working paper No. 12-03. The Food and Agriculture Organization of the United Nations (FAO) Rome. http://www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf (accessed 13 March 2019).

FAO Aquastat, 2013. Siebert, S., Henrich, V., Frenken, K., Burke, J. 2013. *Global Map of Irrigation Areas version 5.* Rheinische Friedrich-Wilhelms-University, Bonn, Germany / FAO, Rome, Italy.

Fischer, G., Nachtergaele, F., Prieler, S., Teixeira, E., Tóth, G., van Velthuizen, H., Verelst, L., Wiberg, D. 2012. GAEZ v3.0 Global Agro-Ecological Zones - Model Documentation. International Institute for Applied systems Analysis (IIASA), Laxenburg and the Food and Agriculture Organization of the United Nations (FAO), Rome. http://typo3.fao.org/fileadmin/user_upload/gaez/docs/GAEZ_Model_Documentation.pdf (accessed 13 March 2019).

Fischer, G., van Velthuizen, H.T., Shah, M.M., Nachtergaele, F.O. 2002. Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. International Institute for Applied systems Analysis (IIASA), Laxenburg and the Food and Agriculture Organization of the United Nations (FAO), Rome. http://pure.iiasa.ac.at/id/eprint/6667/1/RR-02-002.pdf (accessed 13 March 2019).

Foley, JA., Ramankutty, N., Brauman, KA., Cassidy, ES., Gerber, JS., Johnston, M., Mueller, ND., O'Connell, C., Ray, DK., West, PC., Balzer, C., Bennett, E., Carpenter, SR, Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, DPM. 2011. Solutions for a cultivated planet. *Nature* 478, 337–342. DOI: 10.1038/nature10452

Godfray, H.C.J., Garnett, T. 2014. Food security and sustainable intensification. *Phil. Trans. R. Soc. B* 369, 20120273. DOI: 10.1098/rstb.2012.0273

Grumeza, N., Kleps, C. 2005. Irrigation systems in Romania Ceres, Bucharest (in Romanian)

GWP CEE – Global Water Partnership Central and Easter Europe, 2015. Guidelines for the preparation of Drought Management Plans. Development and implementation in the context of the EU WFD, GWP CEE, https://www.gwp.org/globalassets/global/gwp-cee_images/idmp-guidelines-pdf-small.pdf (accessed 6 April 2019).

Hoff, H. 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.

Hydromeliorácie, š.p. Report, 2016 http://www.hydromelioracie.sk/main.php?informacie-o-podniku/vyrocne-spravy.

ICPDR, 2012. Tisza case study on agriculture and water management, https://www.icpdr.org/main/sites/default/files/nodes/documents/trb_case_study_water_and_agric_final_v2.pdf (accessed 6 April 2019).

ICPDR, 2013. ICPDR Strategy on Adaptation to Climate Change, prepared by ICPDR RBMEG with support of the LMU Munich, Vienna.

ICPDR, 2015. The Danube Basin River District Management Plan. Part A – Basin-wide Overview, https://www.icpdr.org/flowpaper/app/services/view.php?doc=drbmp-update2015.pdf&format=pdf&page={page}&subfolder=default/files/nodes/documents/ (accessed 6 April 2018).

ICPDR, 2017. The 2015 Droughts in the Danube River Basin, https://www.icpdr.org/main/sites/default/files/nodes/documents/icpdr_report_on_2015_droughts_in_the_danube_river_final.pdf (accessed 6 April 2019).

INS – National Institute of Statistics in Romania, 2015. Arable land and areas equipped with irrigation infrastructure and irrigated agricultural areas, www.insse.ro (accessed 12 March 2019).

Iglesias, A., Garrote, L. 2015. Adaptation strategies for agricultural water management under climate change in Europe. *Agric. Water Manag*. 155, 113–124. DOI: 10.1016/j.agwat.2015.03.014

Interreg DTP, http://www.interreg-danube.eu/about-dtp/programme-priorities (accessed 2 April 2019).

Jaegermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci*. 19, 3073–3091. DOI: 10.5194/hess-19-3073-2015

Johansson, R.C., Tsur, Y., Roe, T.L., Doukkali, R., Dinar, A. 2002. Pricing irrigation water: a review of theory and practice. Water Policy 4 (2002), p. 173–199omics, University of Northern KTBL, 2013. Freilandbewässerung, Betriebs- und arbeitswirtschaftliche Kalkulationen.

Koncepcia revitalizácie hydromelioračných sústav na Slovensku, 2014. Concept of revitalization of hydro-amelioration systems in Slovakia. Ministry of Agriculture and Rural Development of the Slovak Republic, Material No: 585/2014/100, 2014, 53 p.

Livingston, M.L. 1995. Designing water institutions: market failures and institutional response. *Water Resources Management* 9, 203–220. DOI: 10.1007/bf00872129

Loczy, D., Kertesz, A., Loki, J., Kiss, T., Rosza, P., Sipos, G., Suto, L., Szabo, J., Veress, M. 2012. Recent landform evolution in Hungary, in: Loczy, D., Milos, S., Kotarba, A. (eds.), Recent Landform Evolution: The Carpatho-Balkan-Dinaric Region. Springer, 205–249.

MACSUR, 2017. Global Representative Agricultural Pathways for Europe. http://ojs.macsur.eu/index.php/Reports/article/view/T1.2-XC16.2-D/pdf (accessed 15 March 2019).

MAEP – Government of the Republic of Serbia, Ministry of Agriculture and Environment Protection, 2015a. Water Management Strategy for the Territory of the Republic of Serbia, the 'Jaroslav Černi' Water Management Institute of Belgrade, http://www.mmediu.ro/app/webroot/uploads/files/2016-01-21_Proiect_de_Strategie_eng.pdf (accessed 26 March 2019).

MADR – Ministry of Agriculture and Rural Development in Romania, 2011. The Project of Rehabilitation and Reform of the Irrigation Sector. The Strategy of Investments in the Irrigation Sector – final report, 103p.

MADR – Ministry of Agriculture and Rural Development in Romania, 2016. The National Programme of Rehabilitation of the main Irrigation Infrastructure in Romania, Official Monitor Part I No. 879/02.11.2016, 28p.

Mauser, W., Stolz, R., Weber, M., Ebner, M. 2018. *Danube River Basin – Climate Change Adaptation*, International Commission for the Protection of the Danube River (ICPDR), Final Report, 137 p. https://www.icpdr.org/main/sites/default/files/nodes/documents/danube_climate_adaptation_study_2018.pdf.

Mauser, W. and Prasch, M. (eds.), 2016. Regional Assessment of Global Change Impacts. The Project GLOWA-Danube, Springer. DOI: 10.1007/978-3-319-16751-0

Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., Calzadilla, A. 2015. Global biomass production potentials exceed expected future demand without the need for cropland expansion, *Nature Communication* 6, 8946. DOI: 10.1038/ncomms9946

Mauser, W. 2017. Assessing Danube Futures under Conditions of Global Change. In: Balteanu, D. (ed.) Lower Danube Basin. Approaches to Macroregional Sustainability, Romanian Academy Publishing House, Bucharest, 15–31.

Mauser, W., Hank, T. 2008. Adapting to water scarcity in Europe. Proceedings of the 4th ECRR International Conference on River Restoration, EXPO 2008, 15 p., Zaragoza, Spain.

Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B., Hackmann, H., Leemans, R., Moore, H. 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability, *COSUST*. DOI: 10.1016/j.cosust.2013.07.001

Ministry of Agriculture and Food, 2017. Annual Agricultural Report, http://www.mzh.government.bg/MZH/Libraries/ (accessed 15 March 2019).

Ministry of Agriculture and Food. 2016. A common strategy for the management and development of the hydraulic network and protection from harmful effects of water.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J. 2010. Improving agricultural water productivity: Between optimism and caution, *Agric. Water Manag*. 97 (4), 528–535. DOI: 10.1016/j.agwat.2009.03.023

Müller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J. 2012. Closing yield gaps through nutrient and water management, *Nature* 490, 254–257. DOI: 10.1038/nature11420

Nilsson, M., Griggs, D., Visbeck, M. 2016. Policy: Map the interactions between Sustainable development Goals. *Nature News* 534, 320–322. DOI: 10.1038/534320a

Pistocchi, A., Beck, H., Bisselink, B., Gelati, E., Lavalle, C., Feher, J. 2015. Water scenarios for the Danube River Basin: Elements for the assessment of the Danube agriculture-energy-water nexus (European Commission Joint Research Center Technical Report). Publications Office of the European Union, Ispra. DOI:10.2788/375680 (accessed 20 November 2018).

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I. 2014. Food security and food production systems, in: Contribution of Working Group II to IPCC 5th Assessment Report: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, New York, USA, 485–533.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2010. Global Agricultural Lands: Croplands, 2000. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY (accessed 5 January 2019). DOI: 10.7927/H4C8276G

Romanian Geography Vol. 5, 2005. Romanian Plain, Danube, Dobrogea Plateau, Romanian Littoral and Continental Platform of the Black Sea, Posea, G., Bogdan, O., Zavoianu, I., Buza, M., Balteanu, D., Niculescu, Gh. (eds.), in Romanian language, Romanian Academy Publishing House, Bucharest, 967 p. (in Romanian)

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison, *PNAS* 111 (9), 3268–3273. DOI: 10.1073/pnas.1222463110

Siebert, S., Webber, H., Zhao, G., Ewert, F. 2017. Heat stress is overestimated in climate impact for irrigated agriculture. *Environ. Res. Lett*. 12, 054023. DOI: 10.1088/1748–9326/aa702f

Stefanov, P. 2002. The Moesian hilly plateau-like plain, in: Kopralev, I., Yourdanova, M., Mladenov, C. (eds.), Geography of Bulgaria. Physical Geography. Socio-Economic Geography. ForCom Publishing House, Sofia, 30–31.

Trnka, M., Hlavinka, P., Balek, J., Semerádová, D., Dubrovský, M., Štěpánek, P., Vizina, A., Hanel, M., Žalud, Z., Lukas, V., Dumbrovský, M., Růžek, P., Daňhelka, J., Chuchma, F., Novák, P., Novotný, I., Pavlík, F., 2016. Balancing assessment of available water resources and moisture needs within defined irrigation districts (in Czech language), Státní pozemkový úřad, Brno.

UN – United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf. (accessed 1 May 2019).

Vanham, D., Bidoglio, G. 2014. The water footprint of agricultural products in the European river basins. *Environ. Res. Lett*. 9, 1–11. DOI: 10.1088/1748-9326/9/6/064007

Velikov, I. 2013. Development in agriculture and rural areas of Bulgaria, Friedrich-Ebert-Stiftung Ltd., p.167, Belgrad, Serbia. http://library.fes.de/pdf-files/bueros/belgrad/10399-20131211.pdf (accessed 15 March 2019).

Zabel, F., Putzenlechner, B., Mauser, W. 2014. Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change. *PLoS ONE* 9(9), e107522. DOI: 10.1371/journal.pone.0107522