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CLIMATE CHANGE IMPACTS ON THE WATER RESOURCES IN THE DANUBE RIVER BASIN AND POSSIBILITIES TO ADAPT – THE WAY TO AN ADAPTATION STRATEGY AND ITS UPDATE

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Abstract

As the Intergovernmental Panel on Climate Change reported in 2013, climate change will have significant impacts on all water sectors. Since water is essential for live, culture, economy and ecosystems, climate change adaptation is crucial. Therefore, a legal and political framework was established by the commissions of the European Union, the United Nations and on national levels. For the Danube River Basin (DRB), the International Commission for the Protection of the Danube River got the mandate to develop an adaptation strategy in 2012 and to update this strategy in 2018. The natural science basis on which the adaptation strategy and its update are based on are two studies, conducted in 2011/2012 and updated and revised in 2017/18. Numerous documents from actual research and development projects and studies dealing with climate change and its impacts on water related issues were analysed in detail and the results summarised. It is agreed that temperature will increase basin-wide. The precipitation trend shows a strong northwest-southeast gradient and significant changes in seasonality. Runoff patterns will change and extreme weather events will intensify. However, the magnitude of the results shows a strong spatial variability due to the heterogeneity of the DRB., It is assessed that these changes will have mostly negative impacts on all water related sectors. Based on the scientific findings an approach for an improved basin-wide strategy on adaptation to climate change is developed. It includes guiding principles and five categories of adaptation measures targeting different objectives.

Keywords: Climate Change, adaptation strategy, Danube River Basin, water sector

INTRODUCTION

Climate change will have various impacts on ecosystems and consequently on human life (IPCC, 2007; IPCC, 2013). Impacts on water will cause changes in water availability, water temperature, water quality and in extreme hydrological events like floods and droughts and accordingly trigger changes in all water related areas (IPCC, 2013). Thus, adaptation to these changes will become one of the major challenges of the 21st century in river basins. In order to be prepared for possible consequences of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) asks Parties of the Kyoto Protocol to develop implement and regularly update programmes of measures for climate change adaptation on a national and regional level (United Nations, 1998). Several European and UN directives and guidelines are explaining the necessity of adaptation to climate change and are supporting the development of strategies (EEA, 2017; EC, 2009; UNECE, 2009). Moreover, the EU water framework directive (WFD) requires an integrated river basin management across administrative or political boundaries and demands to consider possible climate change impacts. Nevertheless, adaptation strategies for the large river basins in Europe hardly existed until 2012. Therefore, a programme of pilot projects and a platform for exchanging experience was established to foster the implementation of transboundary adaptation activities in river basins. For the Danube as Europe's second largest River basin, in December 2012 the International Commission for the Protection of the Danube River (ICPDR) adopted the Strategy on Adaptation to Climate Change (ICPDR, 2013), being the first large river basin with a climate change adaptation strategy. An update will be finished by beginning of 2019.

On the way to the ICPDR strategy and its update, one objective is to develop a comprehensive scientific knowledge base that gives an overview of future climate change and its impact in the DRB. To achieve this, a total of 89 and 73, respectively, research and development projects, studies and scientific papers were analysed. This revealed significant, regionally varying changes in all water related sectors. The second objective is to compile a catalogue of adaptation measures suitable for the DRB to meet the challenges of climate change. Basis for this catalogue was the analysis of already existing climate change adaptation strategies as well as close collaboration with stakeholders from the riverine countries, environmental organisations and water dependant industries. Five groups of measures were identified:

preparation measures, ecosystem based measures, behavioural and managerial measures technological measures and policy approaches. The catalogue of measures is made available as a user friendly online tool. The stakeholder dialogue and the analysis of adaptation activities such as National Adaptation Strategies pointed out communalities, options for cooperation and challenges among the countries of the DRB, which need to be further taken into consideration. To make the studies comparable, the same methods (data acquisition, uncertainty assessment) were used. The methodology of the studies and the integration of the results in the ICPDR Strategy on Adaptation to Climate Change and its update are content of this publication.

THE STUDY AREA: THE DANUBE RIVER BASIN

The Danube is Europe's second largest river with a length of 2,857 km from its source in south-western Germany to its delta at the Black Sea in Romania and the Ukraine and can be divided into the Upper Danube River Basin (UDRB) until the gauge Bratislava in Slovakia, the Middle Danube River basin (MDRB) until the Iron Gate at the border between Serbia and Romania, and the Lower Danube River basin (LDRB) from the Iron gate to its delta (Fig. 1). The catchment has a total area of 801,500 km² and encompasses several mountain areas like parts of the Alps, the Carpathian Range and the Dinaric Mountains. The climatic conditions range from temperate zones in the western parts to a continental climate with hot summers and cold winters in the central and eastern basin. The southern and south-western parts are influenced by Mediterranean climatic conditions with warm, dry summers. Furthermore, orographic conditions also determine the climate in the DRB. Average temperature increases from the western parts to the eastern parts of the basin and reaches +12°C in the lowlands of the Sava River, whereas the coldest temperatures can be found on the mountain peaks in the Alps and the Carpathians. Precipitation falls throughout the year and reaches a maximum in the summer months in almost all regions except the south-western parts with long dry periods during summer. However, the amount of precipitation strongly varies in the basin between a minimum of 350 mm/a in the lowlands of the Black Sea and a maximum of 3,500 mm/a in the Alps. The runoff characteristics change along the way through the riparian countries, determined by the passages through flat basins and mountain regions and the climatic conditions. Close to its source in Western Germany, the Danube shows pluvial characteristics which are then altered by the inflow of the rivers from the Alps to a pluvio-nival runoff regime. After the influence of the Inn, the Danube is dominated by snowmelt, changing the regime to a single-peak mountain-snow regime with a maximum in early summer. After the inflow of rivers originating in the Carpathians with a snowmelt peak in spring, and due to the continental climatic conditions with drier summers, the runoff regime of the Danube shows a two-peak maximum from the Carpathian rivers (first) and the Alpine rivers (second), while the minimum in October is coincident. The further inflows of Drava, Tisza and Sava result in a single maximum of the Danube in April and one minimum in October. The regime characteristics of the Danube do not considerably change until the outflow in the Black Sea. The mean average discharge of the Danube increases from approximately 2,000 m³/s in Bratislava, to approximately 5,500 m³/s at the Iron Gate and reaches finally approximately 6,500 m³/s at the Danube Delta, fed by the main tributaries of the rivers Inn, Drava, Tisza and Sava. The DRB provides water resources for 83 million people in 19 countries (Fig. 1), which makes it the most international river basin in the world (ICPDR, 2014). In this region, water is used in

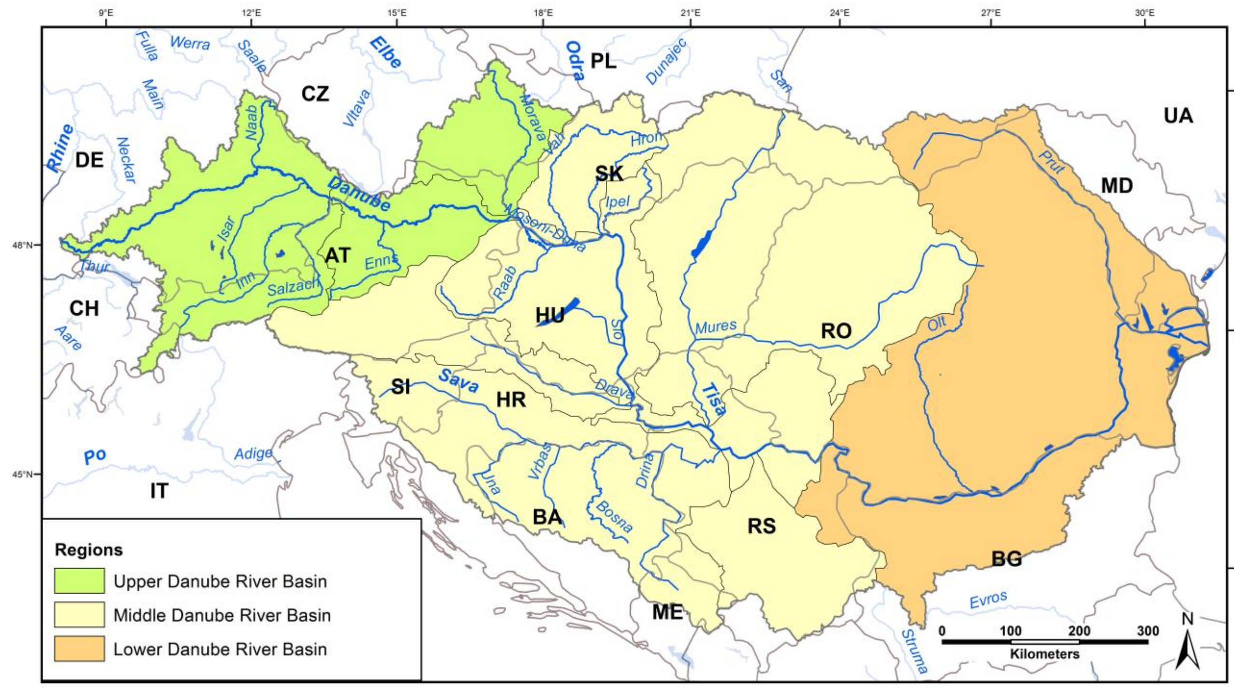

Fig. 1 Main regions of the Danube River Basin

various ways, ranging from agriculture to energy production and navigation. Despite these important water use functions, the Danube River Basin is characterized by a wide range of different natural conditions, contains several highly valuable ecosystems, e.g. the UNESCO World Heritage Site of the Danube Delta as the world's largest wetland and provides habitats for over 2,000 plant species and 5,000 animal species (ICPDR, 2014).

DATA BASE AND ANALYSIS METHOD

In the following the creation of the scientific knowledge base and the methods of assessing the regional impacts of climate change on water-related issues and adaptation activities in the Danube River Basin (DRB) are presented. On this basis the ICPDR Strategy on Adaptation to Climate Change was developed. There have been two project periods. The initial Danube Study was conducted in 2011 and completed in 2012 (Prasch et al., 2012). It provided a comprehensive overview on climate change impacts on the DRB and adaptation measures. The Danube Study was revised and updated in 2018 (Stolz et al., 2018) due to significant developments in climate modelling and new scientific findings concerning the impacts on water related issues. In this project phase only research and development projects, studies and adaptation activities which were conducted between 2012 and July 2017 were taken into account. For means of comparability the same methodology of the analysis and zoning of the DRB were applied in both studies. Only documents, reports and papers which have been published and are accessible through libraries or internet in English, German or French could have been taken into account.

Research and development projects

In order to reach a common, basin-wide understanding of the scale and magnitude of climate change pressures and impacts on water resources, research and development projects and studies dealing with climate change in the DRB or parts of the basin were compiled by online search and participation in conferences and meetings. For the initial Danube Study, 89 projects and studies were selected for the analysis. A detailed list of them can be found in the Annex of the study (http://www.icpdr.org/main/activities-projects/climate-change-adaptation). For the update and revision of the Danube Study documents from 73 projects and studies, published between 2012 and 2017, were included (http://www.icpdr.org/main/resources/climate-change-adaptation-update-danube-study).

In a first step the spatial coverage, the present status of the project (ongoing or finalized), the studied time period and the applied methods are analysed. Projects dealing with climate change impacts in the entire DRB were not available for the initial Danube Study, but the DRB is part of large investigation areas of 25 projects, mostly funded by the European Commission 5th, 6th and 7th framework programmes. For the update and revision of the Danube Study only the study from Bisselink et al. (2018) was available dealing with climate change and its impacts in the entire DRB. Sub-regions or sub-catchments of the DRB are mainly covered by projects and regional studies which are funded either internationally by the Interreg programmes Alpine Space and CADSES (Central Adriatic Danubian South-Eastern European Space) as well as the South East Europe Transnational Cooperation Programme, several EU programmes, the UNDP (United Nations Development Programme), WWF (World Wildlife Fund) and the Worldbank, or nationally, in particular by Germany, Austria, Hungary and Romania.

To make statements about the impacts of climate change comparable the analysis of the used climate models and the modelling periods is of utmost importance. In the analysed documents, mainly the time periods from 1961 to 1990 and from 1971 to 2000 were taken as reference period. The modelled near-future periods vary significantly, but peaking for the period 2021-2050, whereas for the far-future period there is agreement to model the time span 2071-2100.

To assess the future development, models were run under scenario conditions, driven by Global and Regional Circulation Models (GCM resp. RCM), so that the spatial resolution of the simulation results varied between 0.3 and 2° (50-150 km) (GCMs), and between 20 and 50 km (RCMs). The IPCC SRES emission scenarios A1B, A2, B1 and B2 (Nakićenović and Swart, 2000) were chosen and applied as single runs, sometimes as ensemble runs. Some studies applied different dynamical and statistical downscaling methods to analyse the impacts of climate change in a better resolution than provided by the GCMs or RCMs between 1 km and 10 km. In the period from the initial Danube Study to its update the Representative Concentration Pathways (RCPs) (IPCC, 2013) were introduced by the IPCC to replace the SRES emission scenarios. These RCPs were used by some studies which are analysed for the update of the Danube Study.

In a next step, the water related impact fields, which have been investigated by projects and studies were analysed. Therefore, information on future trends of temperature and precipitation and meteorological extreme events were compiled, followed by possible effects on extreme hydrological events, on water availability and quality. In addition, possible impacts on different types of water use and land use like water supply and demand, agriculture, irrigation, navigation, water related energy production and forestry have been considered. And finally, impacts on biodiversity, ecosystems, soils/erosion, limnology and marine coastal zones in the field of ecology were composed.

For the analysis, the above described data are integrated in a database. All findings were classified into statements about the entire DRB, the UDRB, the MDRB and the LDRB (Fig. 1). Commonalities, contradictions and knowledge gaps were identified and finally, the uncertainty of future statements based on the analysed findings was assessed with a newly developed approach, which is presented and discussed in this paper.

Adaptation activities

Similar to the analysis of climate change impacts on the DRB, all relevant information of ongoing, adopted and planned adaptation activities in the water sector in the DRB were compiled and integrated into the data base. The national communications under the UNFCCC (5th or initial, 6th in the update of the study) and available National Adaptation Strategies provide an overview of the present and future impact of climate change and adaptation measures per country and at the EU level (UNFCCC, 2010; UNFCCC, 2014). Additionally, conventions, directives or plans in relation to the EU WFD, relevant reports and further activities on the administrative level in relation to climate change impacts and adaptation activities are considered, i.e. the EEA report (8/2009) "Regional Climate Change and Adaptation: The Alps facing the challenge of changing water resources" (EEA 2009) and EEA report (1/2017) "Climate change, impacts and vulnerability in Europe 2016". A detailed list of all analysed documents can be found in the Annexes of the Danube Studies (http://www.icpdr.org/main/activities-projects/climate-change-adaptation).

In the analysis of the adaptation activities the spatial coverage, the present status of the activity (ongoing or finalized), the possible impacts of climate change and the suggested or adopted adaptation measures are studied. Most activities are limited to single countries. National Communications under the UNFCCC are available for all countries of the DRB. Almost all countries already adopted National Adaptation Strategies (NAS) or are preparing one as illustrated in Figure 2. Conventions, declarations, guidances and programs mainly cover the entire DRB or larger parts of it.

The suggested or adopted adaptation measures of the activities are classified for different impact fields, analogously to the analysed impacts addressed in the analysed research and development projects. Therefore, measures to adapt to changes in extreme hydrological events, water availability and quality, in different types of water use and land use like water supply and demand, agriculture with irrigation, navigation and water related energy production were considered. Measures addressing biodiversity, ecosystems and marine coastal zones were composed in the field of ecology. Additionally, general water related adaptation measures were also considered.

Furthermore, the suggested measures are classified into the categories preparation measures, general measures, ecosystem-based measures, behavioural/managerial measures, technological measures and policy approaches following the UNECE (2009) and the EEA (2010; 2017), despite a sharp separation between these categories is sometimes difficult.

In order to obtain the best possible overview over adaptation activities, the analysis was carried out in close collaboration with experts and stakeholders, e.g. representatives from State Ministries for the Environment, for Hydrology and Water Management or for Regional Studies, from NGOs such as WWF, Global Water Partnership, Danube Environment Forum, and Water Research Centres and Institutes, from the DRB. Therefore, the (preliminary) study results were discussed during meetings, workshops and conferences.

Uncertainty assessment

Projections of future climate change and its impact are always associated with uncertainties (Vetter et al., 2017; Latif, 2011; Deser et al., 2010; Hodson et al., 2012). In order to draw the right conclusions from projections of future climate change for the development of adaptation strategies, it is important to assess the uncertainty of statements from numerous studies which content different methods, areas and time periods. No method exists how to compare the different degrees of certainty or uncertainty in statements. A new and pragmatic approach was developed, attempting to give a reliable estimation of the certainty of a parameter encompassing all projects and studies regarding a certain impact. Many factors are influencing the certainty of the statements about future climate change. For almost all projects and studies, different IPCC SRES emission scenarios and RCPs are

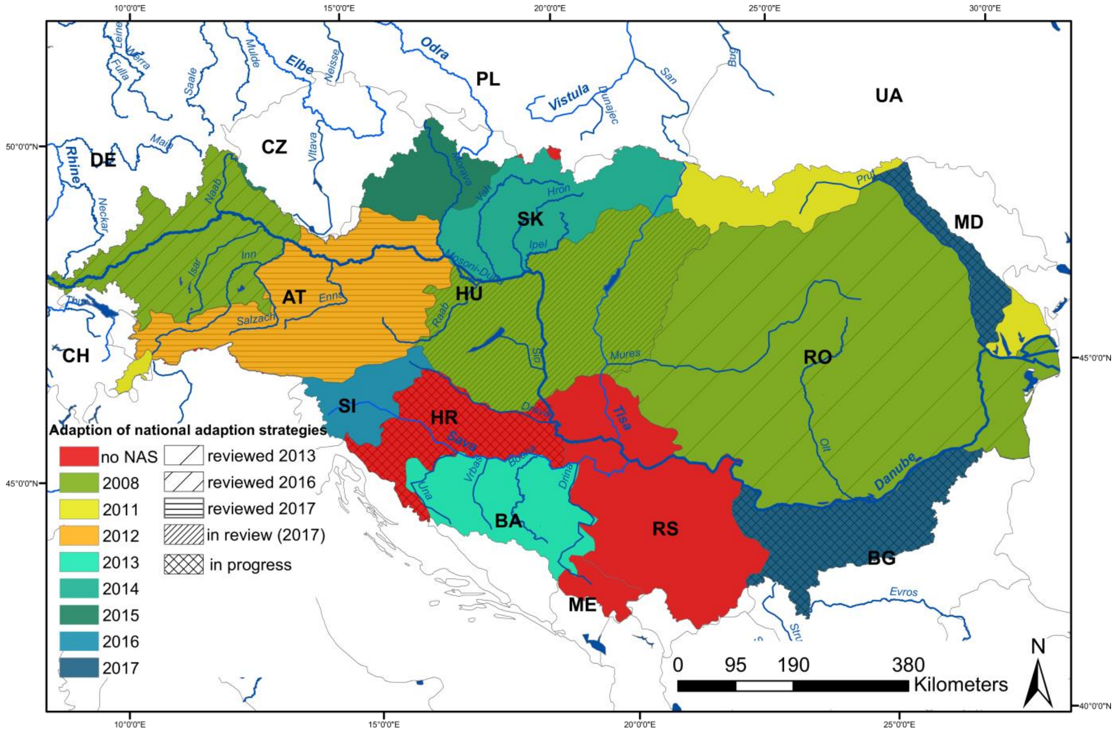

Fig. 2 Countries with National Adaptation Strategies in the DRB (as of 2018)

applied because of different assumptions about future socio-economic development and its consequences for greenhouse gas emissions. The models applied in the studies using the SRES scenarios also have varying outcomes, because of differences in the model structure, the downscaling techniques as well as the spatial and temporal resolution. This is the case for both, climatic and hydrological models. Further uncertainties of the model results are related to differences in validation and analysis methods. These influencing factors of uncertainty are enlarged when analysing several studies. For each impact field a different number of statements/results are available. Some issues are analysed very often, whereas for others only few statements are available. Among the statements itself there are variations, adding further uncertainty. Another source of uncertainty is that different documents frequently analyse different future time periods and use different reference periods. Moreover, different indices, e.g. when assessing floods, are used.

In order to assess the uncertainty of future climate change in this study, three variables are used. First, the statement of certainty for the analysed parameters is taken into account. Second, the level of agreement among the different statements is considered and third, the total number of studies providing statements to a parameter is included. Each certainty-category was calculated by the cube root of the product of the three variables presented by eight values (Fig. 3). If the agreement of the statements (x-axis), the certainty information (y-axis) and the number of studies analysed (diameter of circle) are large the impact is large and the overall certainty is categorized as very high, indicated with a green colour. However, if the number of projects is high, but the agreement of the certainty statement is low, the overall certainty is medium (yellow-orange), and if all three categories are low, the overall certainty is consequently low (red). This practical approach to provide an overall certainty category to the analysed parameters allows the consideration of the, partially little, available information about uncertainty when gathering information from several projects, which apply varying methods. Although this approach is simple, the resulting illustration in Figure 3 enables the comparison of the certainty of the analysed parameters. Nevertheless, this is a practical approach without a detailed statistical analysis, which is not possible because the available information from the analysed projects is mainly given in "soft" variables and not by numbers.

Figure 3 presents the revised and updated overview of certainties for projected climate change impacts of the analysed sectors in comparison to the certainties identified in the initial Danube Study. It has to be noted that forestry, agriculture, flood, low flow and runoff are located at the same similar certainty level, which is represented by the black dot. Although there is a different amount of publications available in the two studies, Figure 3 shows clearly that the degree of certainty increased significantly for most of the analysed water related issues. In the updated study, the scientific statements concerning the future development of precipitation led to a differentiation between mean annual precipitation and precipitation seasonality. It is highly certain, that seasonality changes, whereas the development of mean annual precipitation is unclear for the near future and reliable statements are only made for the far future.

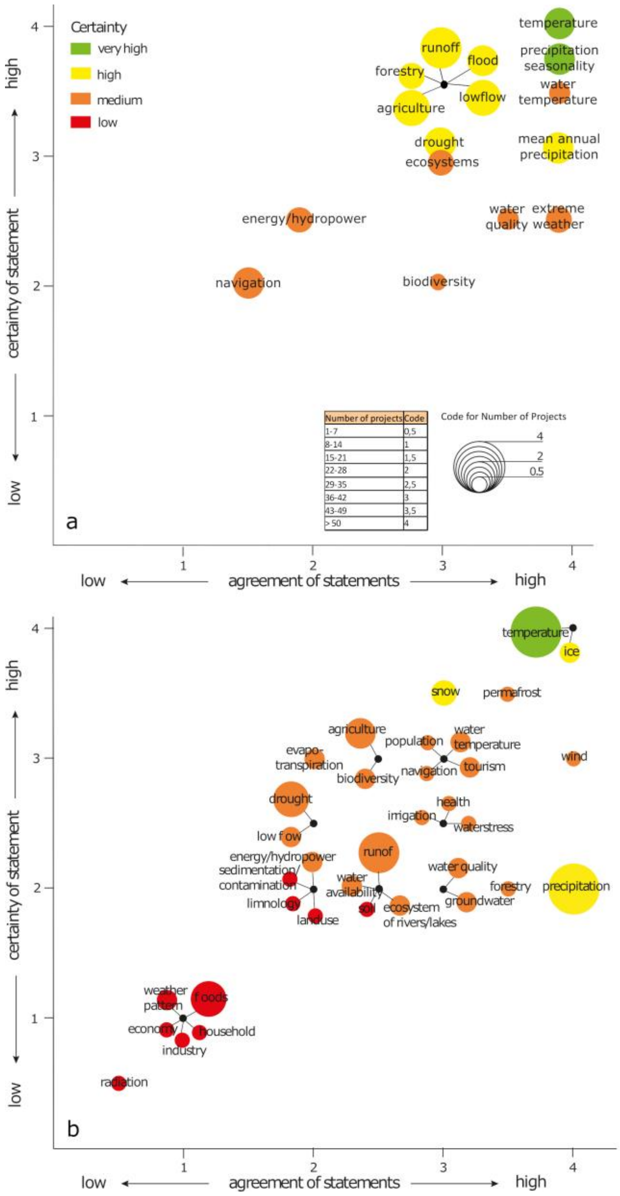

Fig. 3 Uncertainties identified in the update of the Danube Study (a) in comparison to the uncertainties identified in the initial Danube Study (b) (Revision and Update of the Danube Study, Final Report 2018). The legend of a also applies to b.

The certainty of impacts on navigation, ecosystems and biodiversity did not improve in comparison to the initial Danube study due to contradictory and vague statements. It has to be noted that not all water sectors analysed in the initial study are analysed in the update as well. Reasons therefore are that an insufficient amount of new finished projects and data dealing with these topics were published in the last five years.

A high level of certainty may allow the preparation of adaptation measures at an early stage and/or with more detail, whereas a low level of certainty may lead to more general types of measures (e.g. no-regret measures or win-win solutions).

RESULTS

In this chapter, the results from the updated Danube study are presented and differences to the initial study are highlighted. The results are solely based on the analysed studies, projects and adaptation activities that are described above. Furthermore, other factors such as social, demographic, and economic development are crucial for future adaptation strategies to climate change. However, they were not subject of the present study, but are indirectly considered in the analysed scenarios.

Future climate change in the DRB

The trend of a future increase in annual and seasonal air temperature with a gradient from northwest to southeast which was identified in the initial Danube Study is largely confirmed by the update of the Danube Study. This trend is highly certain and can be regarded as a hard fact. Since climate change does not stop at boarders and effects of climate change may largely vary within country borders (due to varying physiographic properties), for the update of the ICPDR Strategy on Adaptation to Climate Change it was decided to show the temperature and precipitation projections of the EURO-CORDEX project. The EURO-CORDEX ensemble runs are based on the new RCPs and provide data on a resolution of 0.11 degree (~12.5km) (Jacob et al., 2014). Thus it is possible to draw a more detailed picture of spatially distributed temperature and precipitation trends, which in turn serves as a sounder basis for the development of adaptation measures and strategies. Results from EURO-CORDEX projections use the period 1981-2010 as reference and define 2021-2050 as near future and 2071-2100 as far future. The range of increase of annual mean temperature for the near future period is between 1.1°C and 1.5°C and for the far future period 3.6°C and 4.7°C under RCP8.5 (Fig. 4). These figures show pronounced warming hotspots in mountain regions and in southeast Europe. Like in the initial Danube Study, EURO-CORDEX projections show, that the annual (Fig. 4a,b) and the summer (Fig. 4c,d) temperature increases are likely to be larger than the winter temperature increase (Fig. 4e,f).

The DRB is located in the transition zone between expected increasing (in Northern Europe) and decreasing (in Southern Europe) future precipitation. Documents analysed in the update of the Danube study confirm this general trend of wet regions becoming wetter and dry regions becoming drier (Fig. 5). The trend is more

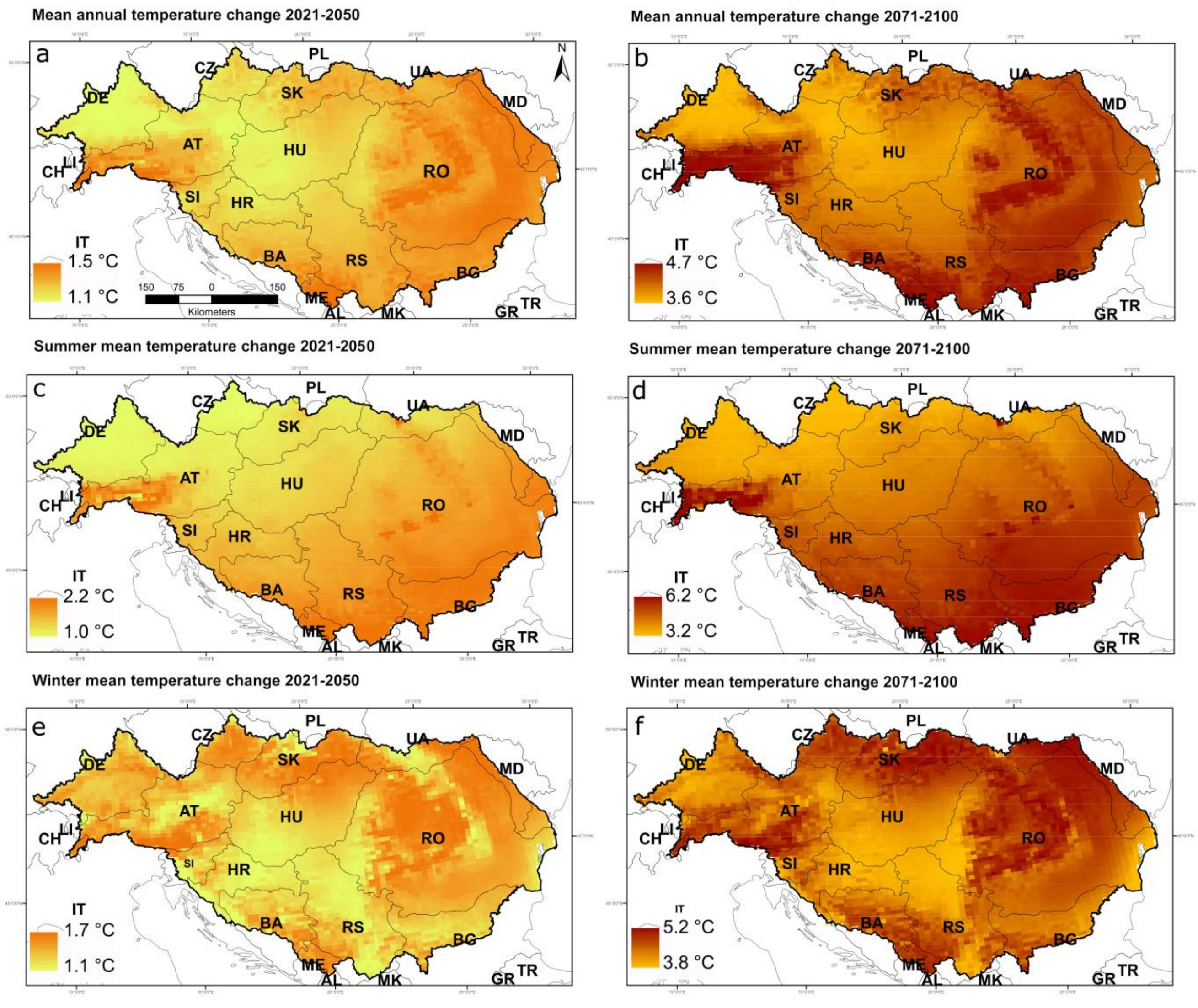

Fig. 4 Change of mean annual (a, b), summer (JJA) (c, d) and winter (DJF) (e, f) temperature in the Danube River Basin for 2021-2050 and 2071-2100 according to the EURO-CORDEX ensemble results under RCP8.5

obvious in the second half of the century. Although the mean annual precipitation in many regions will probably remain almost constant, a tendency for the next decades towards more precipitation (than in the last decades) in the northern parts of the basin and less precipitation in the southern parts is apparent (Fig. 5). The general trend of wet regions becoming wetter and dry regions becoming drier is also reflected in the alpine region, where the already drier south-eastern part of Austria is likely to become drier.

According to the documents analysed in both Danube Studies, trends in mean annual precipitation are rather insignificant until the middle of the century and become significant until the end of the century. However, the most significant change is projected in seasonal precipitation distribution. The summer months are likely to become drier (up to -58%) (Fig. 6) whereas the winter months show a tendency for increasing precipitation (up to +34%) (Fig. 7). The numbers indicate the maximum expected decrease and increase for larger regions in the Danube River Basin but numbers in particular regions may vary largely. The figures display the precipitation change from the EURO-CORDEX initiative in mm relative to the reference period 1981-2010. The comparatively clearest trends are increasing winter precipitation in mountain regions and decreasing summer precipitation in regions already suffering from too little precipitation. On the other hand, there are regions where summer precipitation is projected to increase due to increased frequency of thunderstorms and short heavy precipitation events. As for temperature trends, studies that are based on the newly implemented RCPs like from Bisselink et al. (2018) mostly confirm previous results. Furthermore, data from the EURO-CORDEX initiative provides a more detailed picture of spatially distributed trends.

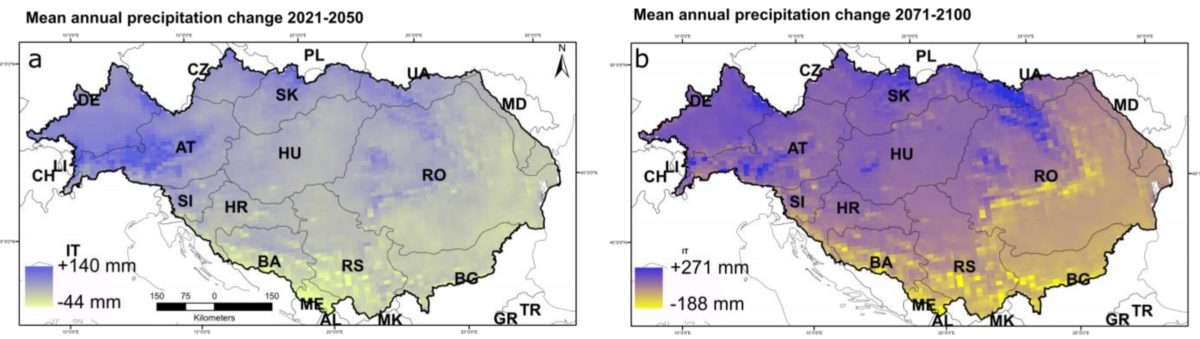

Fig. 5 Change of mean annual precipitation in the Danube River Basin for the periods 2021-2050 (a) and 2071-2100 (b) according to the EURO-CORDEX ensemble runs under RCP8.5

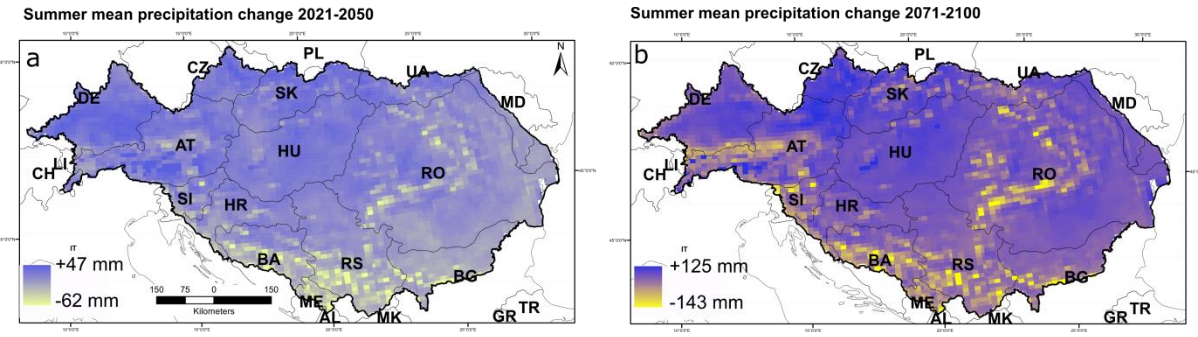

Fig. 6 Change of mean summer (JJA) precipitation in the Danube River Basin for the periods 2021-2050 (a) and 2071-2100 (b) according to EURO-CORDEX ensemble runs under RCP8.5

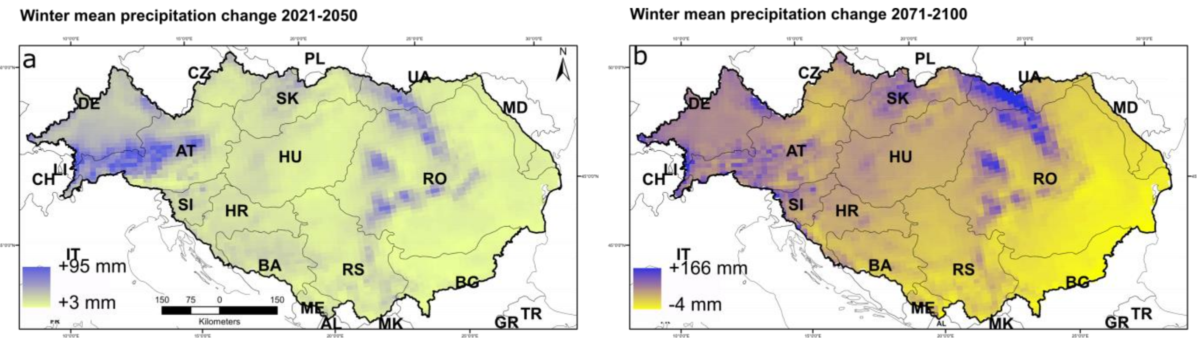

Fig. 7 Change of mean winter (DJF) precipitation in the Danube River Basin for the periods 2021-2050 and 2071-2100 according to EURO-CORDEX ensemble runs under RCP8.5

A future increase in extreme weather events is expected for the whole DRB. The simulations show both, a future increase in the intensity and frequency of dry spells, hot days and heat waves, as well as local and regional increases in heavy rainfall, although the latter is uncertain in spatial and temporal localisation. For the UDRB, an increased risk of storm-related heavy precipitation with high wind speeds is assumed. For the MDRB, it is expected that the occurrence of extreme precipitation days will be intensified in winter and reduced in summer. Due to the warming trends for the whole basin, fewer frost days are expected in winter. Generally, statements from the initial Danube Study are confirmed by the update. Nevertheless, most recently analysed documents show a more pronounced trend towards seasonality in the occurrence of extreme events. Therefore, the agreement concerning an increasing number of extreme winter precipitation events over Europe and especially in the North-East for the far future period must be emphasised. Statements regarding extreme summer precipitation especially in Eastern Europe are inconsistent.

Climate change impacts on water related issues in the DRB

The potential future climatic conditions in the DRB described above will impact the water resources and water-related issues. In the following the expected main impacts on each water sector according to the analysis of the studies are described and compared in a qualitative way. As for future climate conditions, the results of the updated Danube Study are presented and differences to the initial Danube study are highlighted (ICPDR, 2012; ICPDR, 2018).

(1) Water availability

In contrast to the initial Danube Study, most of the documents analysed in the update expect insignificant changes in mean annual runoff until the middle of the 21st century. However, they confirm a significant decrease in mean annual runoff until the end of the 21st century. This is valid for the entire DRB, also for the UDRB. Although this is the area with the highest water availability, water shortages are expected in unfavourable areas in the far future, which has not been reported in the initial study. The most crucial aspect regarding runoff is the change in seasonality, which applies to all of the regions in the DRB. Here, a decrease in summer runoff and an increase in winter runoff are expected due to shifts in precipitation seasonality. Changes of runoff conditions are in turn assumed to cause a decline in groundwater storage and recharge, particularly in summer. The already monitored decline of the past in the Hungarian Great Plain Area is likely to intensify in the future. Lake levels might decrease in summer. Furthermore, a decrease in soil water content is likely in the DRB, particularly in summer.

(2) Water use

The described possible future changes of water availability, extreme hydrological events and water quality will influence water use. Water demand is expected to increase in a warmer climate in agriculture, industry, energy production and general human consumption. In the field of agriculture more water might be required for livestock and irrigation, because of drier summers and a longer growing period because of higher temperatures.

The possible shortening of the growing season due to too high temperatures in the south-eastern DRB will increase the water demand for irrigation

The most remarkable difference in comparison to the initial Danube Study is that now negative impacts of climate change on agriculture are expected to exceed positive impacts in every sub region. Positive impacts like higher yields due to a longer vegetation period are now largely limited to the short and medium term future. In the far future the higher temperatures are affecting the vegetation period negatively. Moreover, a higher atmospheric CO_2 content is no longer mentioned as a positive factor for agriculture. Impacts which affect both, agriculture and forestry are a shift in species, invasive species, and pests, changing species composition and damages from extreme weather. In contrast, damages from snow and frost are assumed to be less. A changing climate will affect power generation as well. The reduced water availability in summer in combination with projected increasing water temperatures might become problematic for thermal electricity production, which is dependent on cooling water from rivers. Hydroelectric power generation is likely to decrease in the DRB on average and in summer, whereas in winter an increase due to more rain than snowfall is possible. However, hydropower generation in rivers may face problems due to flood events increasing in intensity and frequency and the resulting damages (Frik, 2018; Steininger et al., 2015). Additionally, a seasonal shift in power generation might be triggered by changing water availability, above all in mountain regions. The Danube is an important water way in Europe. Hence navigation may face challenges due to climate change effects on runoff conditions. While in winter navigation conditions might improve with less icing and higher water levels, in summer low flow conditions are likely to limit cargo loads and in worst case make the Danube impassable, just as it happened during this summer and autumn. The update of the Danube Study shows that increasing flood conditions are expected to be problematic for navigation. Possible consequences of this scenario are industrial production losses as well as increased difficulties in accessing water resources and higher costs for water resource use. Also conflicts between the different water users could arise and require potential solution options as for example, a hierarchy of water supply during water scarcity periods.

An increase in air and water temperature, combined with changes in precipitation, water availability, water quality and increasing extreme events may lead to changes in ecosystems, life cycles, and biodiversity in the DRB in the mid- and long-term. The habitats and ecosystems in the south-eastern region of the DRB and in the Hungarian Great Plain area are especially likely to become drier. As consequences, a rearrangement of biotic communities and food webs, the disappearance of species and the invasion of species might occur. Shifts and changes in aquatic and terrestrial flora and fauna, particularly in littoral communities and aquatic systems are likely. In the marine coastal zones, a redistribution and losses of marine organisms as well as the increase of invasive species and in toxic bloom events are possible impacts of rising sea surface temperatures. Higher sea levels could increase the salinization of estuaries and land aquifers and change ecological conditions at the coast of the Black Sea. Potential increasing water demand, e.g. irrigation for agricultural purposes in the entire DRB, especially in the south-eastern parts, may also deteriorate the ecological and chemical balance of freshwater bodies and could lead to an increase of contaminated surface and groundwater bodies.

Besides climate change impacts, anthropogenic impacts, political regulations and restrictions as well as the technological development will also trigger future changes in water quantity and quality in the DRB.

Comparing the results of both studies, the developments in climate change modelling and the resulting findings, show the necessity of an update of the scientific knowledge base, which is the basis for a successful implementation of adaptation measures and strategies.

Less water availability in summer is likely to cause longer, more frequent and more intense drought and low flow situation in the DRB. Particularly the south-eastern parts of the DRB, namely the Carpathian Area, the southern parts of Hungary and Romania, the republic of Serbia, Bulgarian and the Danube Delta region are likely to be confronted with severe droughts and water shortages. Contrary, there is no future trend for droughts in the Alpine head watersheds. However, a spread of affected areas to the north is expected. Like drought and low flow events, flood events in the DRB are expected to intensify and occur more often. The update of the Danube Study confirms statements of the initial study. Small and mountain catchments appear to be the most affected ones. With an increase of torrential rainfall an increase in flash floods is expected despite uncertainties.

Besides water quantity, also water quality is likely to be affected by climate change in the DRB. Increasing air temperature might cause increasing water temperature in the DRB. This in turn will change all temperature dependent chemical and biological processes and cause reduced water quality, especially during droughts in summer.

Adaptation measures for the water sectors of the DRB

To respond to the challenges created by climate change and the water related impacts, it is of great importance to consider the consequences which today's actions may cause as late as during the next 50 – 100 years. This needs adaptation strategies which are more ambitious than up to now. Nevertheless, there is consensus between the Danube countries and the European Union that adaptation to climate change is a central environmental policy issue. Due to the transboundary character of water and its relevance for various issues and water-related sectors such as its role for biodiversity and the ecosystem, energy, transport, agriculture, floods and droughts, integrated river basin management is key for an approach to climate change adaptation.

In this section, possible adaptation measures for the impacts of climate change on the water sector of the DRB as suggested by the analysed adaptation activities are presented. Measures with a high common agreement are selected. This means that they have been suggested by most of the analysed documents. Furthermore, they are valid for almost all impact fields. Adaptation should start with a priority on win-win, no-regret and low-regret measures that are flexible enough for various conditions. The adaptive approaches require enough flexibility so they can also be modified and adapted to local conditions. This way of working has the benefit of increasing resilience and decreasing vulnerability for the whole Danube ecosystem.

The adaptation measures can be classified into five different categories, targeting different objectives. Preparation and technological measures are aiming on monitoring and infrastructural issues; eco-system based measures should enhance the capacity of eco-systems to adapt, whereas behavioural and managerial measures aim to raise awareness and to encourage knowledge exchange. Policy approaches are most important for basin-wide transboundary solutions. Table 1 gives an overview on these measures. They are classified in the different categories, introduced above.

The smoothly formulated measures allow various realisations and there is no sharp separation possible between the categories of the measures. However, the measures not only have overlapping fields and linkages between the categories, but they are also linked between affected sectors and other relationships such as upstream – downstream dependencies. Positive and negative effects among them may be possible and conflicts may occur, even though the selected measures are no-/ low-regret or win-win-options, so that they have positive effects whatever the extent of future climate is, or other social, environmental or economic benefits are also met (European Climate Adaptation Platform, 2018). For instance, the expansion of protection areas as ecosystem based measure and policy approach could be conflicting with the construction and modification of infrastructure as technological measure, albeit environmental issues are likely to be considered in the adjustment of infrastructure and synergy effects might be found. An increase in water retention areas can lead to higher groundwater recharge, a reduction of flood peaks and positive effects for biodiversity, so that various sectors may profit such ecology with enabling biodiversity, navigation with reduced flood peaks or water related energy production with reduced losses during a flood. To prevent possible conflicts and to foster common goals, cross-sectoral, interdisciplinary and integral approaches and continuous communication, also among the Danube countries are necessary. Furthermore, the time horizon of the effects of adaptation options should be taken into account. While the long-term measures, e.g. reforestation, affect water retention not until several decades, short-time measures, e.g. water-saving techniques may be immediately effective.

Besides the presented measures, there are numerous options for adaptation to climate change, particularly for distinct sectors. The spatial coverage for applying adaptation measures ranges from local to catchment wide actions. In many cases coordination among bordering countries is of great necessity. The principal obstacles to

Table 1 Common adaptation measures to climate change impacts in the water sector in the Danube River Basin (ICPDR Strategy on Adaptation to Climate Change 2018 in preparation)

Preparation measures
Additional, intensified monitoring activities to follow and assess climate change and climate change impacts
Homogenous data production, digital mapping and a centralised database for data exchange and comparability among regions and countries
Identification of potential risk areas and hot spots
Implementation of forecasting and warning services (e.g. for extreme events such as floods and droughts)
Development of action plans or integration of specific issues into ongoing planning activities (e.g. to deal with water scarcity and flood situations)
Further research to close knowledge gaps, determine vulnerability or reduce uncertainty
Rules for water allocation in case of water scarcity under the aspect of benefit sharing
Toolbox preparation measures
Ecosystem based measures
Taking environmental implications and the conservation of biodiversity into consideration in all other measures
Sustainable management of land use practices for improving resilience, and for enhancing the capacity to adapt to climate change impacts
Implementation of green infrastructure to connect bio-geographic regions and habitats
Protection, restoration and expansion of water conservation and retention areas
Rehabilitation of polluted water bodies
Behavioural and managerial measures
Support education, capacity building, awareness raising, information exchange and knowledge transfer
Establishment of and support for an integrated risk management
Support of a water saving behaviour
Propagation of best practice examples
Application of sustainable methods (e.g. good agricultural practices)
Technological measures
Adjustment of (existing) infrastructure, e.g. construction and modification of dams and reservoirs for hydropower generation, agriculture, drinking water supply, tourism, fish-farming, irrigation and navigation
Development and application of water-efficient technologies
Efficient waste- and sewage-water treatment and water recycling
Policy approaches
Support of an institutional framework to coordinate activities
Harmonisation of international, basin-wide legal limits and threshold values
Implementation of restrictions (e.g. for development in flood risk areas)
Expansion of protection areas (e.g. for drinking water resources)
Adaptation of policies to changing conditions

install adaptation measures documented are a lack of knowledge, trained staff, reliable data and financial resources.

For a detailed listing of adaptation measures it is referred to the Danube Study (2012) and the update of the Danube Study (2018). To make the large number of measures better usable for stakeholders, an easy to use online toolbox is created. The toolbox allows the user to obtain detailed information on the measures of interest, which are divided into various groups such as impact fields, relevancy to the WFD, time horizon and others.

CONCLUSION AND OUTLOOK

Climate change will affect water resources in all parts of the DRB as the analysis of existing studies and research and development projects shows. Despite all water sectors and regions are affected, the effects of climate change vary depending on the region. This is due to the landscape diversity as well as the huge east-west and north-south gradient in the DRB. Therefore, adaptation measures have to be flexible enough to react to these heterogeneities. To deal with the uncertainties that come along with projections of future climate we presented a pragmatic approach to show the related uncertainty of the future development to the analysed climate parameters and impact fields. The update of the Danube Study confirmed the trends detected in the initial Danube Study., The improved climate models and modelling approaches (EURO-CORDEX) substantiate the results of the first Danube study. Temperature and precipitation development can be depicted in a higher resolution and with a higher certainty. Impacts of climate change on water related issues will be even more significant in almost all water sectors along with a stronger negative trend than in the first study.

The new certainty analysis shows a significant increase in certainty for most of the water sectors. Temperature development and seasonality in precipitation even tend to be highly certain. Despite all heterogeneities, climate change affects all regions and does not stop at national borders. Water connects all riverine countries, which is why a common strategy is highly important for a successful adaptation to climate change effects. Being a frontrunner and pioneer among transboundary river basin commissions in climate change adaptation activities, the ICPDR adopted the first ICPDR Strategy on Adaptation to Climate Change in the year 2012. Basis therefor was a comprehensive overview about future climate change in the DRB and its impacts on the water sectors as presented in the previous sections. Moreover, it was necessary to collect and analyse already existing adaptation strategies and actions. In order to get the most comprehensive overview possible, experts and stakeholders were consulted additionally. At the Danube Ministerial Meeting in February 2016 Ministers asked the ICPDR to foresee an update of its strategy. During the development of the update of the ICPDR Strategy on Adaptation to Climate Change in 2018, the following points emerged as highly relevant and have to be taken greater into account. First, the strategy needs to be developed in close collaboration with stakeholders, experts and country representatives. This increases acceptance and fosters the implementation. Second, the strategy is developed as a reference document that may be used by countries, regions, and organisations to develop their own individual adaptation strategy. In this context, we developed an online toolbox, which provides a huge amount of adaptation measures. Third, clear goals of the strategy need to be defined in order to make it more powerful. Fourth, the strategy is considered to be a "living" document. This means that it will be updated regularly in order to include the latest scientific results and experiences with the strategy. The principal objective is building resilience against climate change impacts on water resources through capacity building, transboundary cooperation and encouraging basin-wide approaches as well as benefit-sharing is a key priority and objective to address climate change in the Danube River Basin. Base is the update and revision of the Danube Study. Despite most of the results regarding climate change and its impacts from the initial study could be confirmed, science made advances in climate modelling allowing for more detailed climate change projections. This is particularly important for the highly heterogeneous DRB. Along with this, uncertainties could be decreased, which is highly relevant for planning and taking adaptation measures. Moreover, the continuous dialogue with experts, stakeholders and country representatives allowed identifying strengths and weaknesses of the existing strategy. Strengths are that it represents the first existing overall guideline for adaptations in a large catchment and gives an overview on climate change and its impacts in the entire DRB. In contrast to the strengths it shows no clearly addressed objectives and contains no summary for policy makers.

During the initial Danube Study as well as during the update some shortcomings had to be faced which made it quite challenging to create a comprehensive scientific database for an adaptation strategy in the DRB. A meaningful comparison of documents about climate change or adaptation was made difficult, since documents were not available, not available in English, or did not fulfil scientific standards. For some parts of the DRB there exist almost no studies about climate change and its effects on the water sector. Comparability was even made more difficult by the fact that methods and data used in the analysed documents are highly diverse and standards are not met. Moreover, international and interregional collaboration and also collaboration between institutions within one country could be expanded. When it comes to the implementation of adaptation measures, it has to be considered, that measures in one sector may have retroactive, positive or negative effects on one or more other sectors or even other regions or countries. To prevent possible conflicts and to foster common goals, cross-sectoral, interdisciplinary and integral approaches as well as trans-regional/national agreements are necessary. Integral approaches also aim to enhance synergy effects which should be sought. An example of a synergy effect is an increase in water retention areas which can lead to a higher groundwater recharge, a reduction of flood peaks and positive effects for biodiversity.

The updated ICPDR Strategy on Adaptation to Climate Change and the web-based toolbox provide a significant improvement. It increases the applicability of the strategy and gives the stakeholders support for the development of regional and national adaptation solutions. Furthermore, it underlines the necessity of transboundary and trans-sectoral collaboration and emphasizes the importance of specific adaptation measures depending on the characteristics of the sub-catchments.

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