EnviroGRIDS – FP7 European project

Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development

Deliverable 5.8 Synthesis of vulnerability and adaptation issues

Creator	UNIGE
Creation date	1/3/2013
Date of last revision	31/3/2013
Subject	Climate Change and Agricultural Water Resources - A Vulnerability Assessment of the Black Sea Catchment
Status	Final
Type	Word document
Description	This agricultural water vulnerability assessment aims at identifying the most vulnerable regions in the Black Sea catchment. The assessment framework is based on a combination of the DPSIR framework and the vulnerability concept as defined by the IPCC.
Contributor(s)	Bär Roger (UNIGE); Lehmann Anthony (UNIGE); Rouholahnedjad Elham, Abbaspour Karim (EAWAG)
Rights	Public
Identifier	EnviroGRIDS_D5.8 Agricultutal Water Vulnerability Assessment
Language	English
Relation	EnviroGRIDS_D5.2_Baseline analysis of agri-environmental trends, impacts and vulnerabilities EnviroGRIDS_D5.3_Vulnerability and adaptation issues

Abstract:

Agriculture in the Black Sea catchment is responsible for a considerable share of the area's total water withdrawal and the majority of its total water consumption. It therefore plays a key role in sustainable water resources management. However, in the future water resources might be threatened considerably due to climate change. Precipitation and temperature changes will not only modify water availability for rainfed agriculture, but will also impact irrigation capacity.

This vulnerability assessment aims to identify the most vulnerable regions and to explain why these regions are considered to be vulnerable. The assessment framework is based on a combination of the DPSIR framework and the vulnerability concept as defined by the IPCC. Three different climate change scenarios are used for the assessment: 1) An increase in temperature; 2) A decrease in precipitation; and 3) A combination of the first and second scenarios. The data for this assessment is derived from a SWAT model that has been set up in the enviroGRIDS project.

The results show that the regions of the Black Sea catchment are impacted by climate change differently. Some countries benefit from climate change, while others encounter considerably worse agro-climatic conditions in future. Notably, Turkey experiences severe water stress, whereas mountainous regions benefit the most from higher temperatures. Additionally, natural plant growth conditions mostly improve due to more suitable temperature conditions. In contrast, the deteriorating agricultural conditions mainly result from a diminishing irrigation potential that is caused by reduced precipitation.

The conclusion emphasises the important role of the legal framework as well as more sustainable agronomic practices and proposes improvements for future assessment methods in this research field.

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Abbreviations

CC	Combined Change
ET	(Actual) Evapotranspiration
DPSIR	Driver-Pressure-State-Impact-Response
IPCC	Intergovernmental Panel on Climate Change
HRU	Hydrological Response Unit
OECD	Organization for Economic Co-operation and Development
PC	Precipitation Change
PET	Potential Evapotranspiration
PSR	Pressure-State-Response
RD	Recorded Data
SWAT	Soil and Water Assessment Tool
TC	Temperature Change
WFD	Water Framework Directive

1. Introduction

1.1 Climate Change and Water Resources

1.1.1 Climate Change and Agriculture

In the present-day, climate change is a widely acknowledged fact. Climate change will not only affect global average temperatures, but it will also result in precipitation pattern changes. Most notably, it will lead to more weather extremes such as droughts and heavy precipitation (IPCC 2007).

Climate change will have a considerable impact on agricultural production and its related processes (EEA 2004) since climate is one of the most important natural factors affecting agriculture (Shengcai et al. 2012). Positive effects, such as an increase in temperature, may allow for earlier sowing, decrease the risk of freezing, and enhance plant productivity (EEA 2004). Additionally, the rising concentration of carbon dioxide in the atmosphere could have a positive impact on agricultural production due to its fertilizing effect (van der Weijden et al. 2011; EEA 2004). Nonetheless, climate change can equally have negative effects. Poor harvests may notably result from the increasing frequency and intensity of the aforementioned weather extremes as well as climate related increases in pests and diseases (IPCC 2001).

In the context of climate change, water resources will play a key role. The reason for this is simple: “Crops and livestock need water to grow, and lots of it” (WWAP 2012:12). Climate change will be mainly experienced through the water regime (FAO 2008) and the availability of water resources will be affected by changes in rainfall distribution, soil moisture, glacier and ice/snow melt, and river and groundwater flow. Thus, it is likely that such climate change-induced hydrological changes will affect both the extent and the intensity of rainfed as well as irrigated agriculture (FAO 2008).

1.1.2 Competing for Water

Water is used in numerous ways by many different users. Five major water use sectors are usually distinguished when breaking down human demand for water resources: 1) Food and agriculture; 2) Energy; 3) Industry; 4) Human settlements; and 5) Ecosystems

(WWAP 2012b). It is important to note that the water withdrawals and water consumption rates of these sectors can differ considerably.[1]

Water requirements in the **energy** sector mainly concerns water usage for cooling in thermal power plants and for hydroelectric plant reservoirs. In both cases, considerable amounts of water might be required. These quantities are expected to increase substantially since the EIA (2011) estimates a growth in global energy consumption by approximately 49% from 2007 to 2035.

Water use by **industry** is generally reported to constitute 20% of the world's fresh water withdrawal (WWAP 2009). The quantity of the withdrawn water is usually much greater than the quantity of water it actually consumes (WWAP 2012b). However, effluent discharge originating from the industrial sector can significantly reduce the water quality. This might lead to a substantial reduction of water resources if the polluted water is not treated and therefore unsuitable for re-use.

Human settlements are responsible for 10% of global water withdrawal (WWAP 2009). Their demands can lead to excessive extraction of ground water located in upstream areas of the watershed and subsequently deprive other downstream users and compromise ecosystem functions (WWAP 2012b). As urban populations are projected to increase by 2.9 billion from 2009 to 2050 (UN-Habitat 2006), urban water use will certainly gain importance.

The water demand of **ecosystems** is determined by the water requirements to sustain or restore the services that we want the ecosystem to supply. Water demand is therefore coupled with identifying ecosystem "deliverables", valuating these services and managing water accordingly (WWAP 2012b). Quantifying this demand, however, is difficult.

Water use for **agriculture** is of particular importance since water is indispensable to food security. Irrigation accounts for more than 40% of global production on less than 20% of cultivated land (WWAP 2012b). In other words, although most of the water consumed by agriculture is green water[2], irrigation is essential for global food production.

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[1] Water withdrawal is not to be confounded with water consumption. The former, is water that is withdrawn from a water source, but might be returned to the source after its use. Water consumption, however, is water that is effectively consumed (evaporated, transpired or incorporated into a product) and thus no longer available for subsequent use. (Chapagain et al. 2011)

[2] Green water is the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. (Chapagain et al. 2011)

Furthermore, global irrigation water consumption is estimated to increase by 11 % between 2008 to 2050 (FAO 2008).

Water withdrawal for agriculture varies considerably between different regions and countries. Nevertheless, in many countries it accounts for the main part of the total water withdrawal and can reach up to 98% (FAO 2013). This is of particular importance since the agricultural sector as a whole has a large water footprint compared to other sectors (WWAP 2012b). The consumption includes water consumption for food crops, fib and feed production (transpiration), plus evaporation losses from the soil and from open water associated with agriculture, such as rice fields, irrigation canals and reservoirs (FAO 2008). Furthermore, agricultural production also affects water quality, which in turn reduces its availability (WWAP 2012b). In short, unlike many other types of water use, most of the water used for agricultural production is consumed and therefore not available for further use.

The current and future water demands of the aforementioned sectors are driven by several external forces (e.g., demographic changes, technological developments, economic growth, social and cultural values) that are not necessarily the same in all sectors (WWAP 2012b). Water use in human settlements, for instance, might be driven mainly by demographic developments, whereas industry's use might be driven more by economic developments. However, regardless of the future water demand of those sectors, climate change and potential physical water scarcity will in either case affect all of them. As a result, competition for the available water resources is likely to intensify in the future.

1.1.3 Sustainable Water Resources Management

The challenge of an impending water crisis has already been recognized in the *Dublin Statement on Water and Sustainable Development* (also known as the *Dublin Principles*) in 1992. Since then the necessity for sustainable water resources management is generally acknowledged.

> *Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.* (ICWE 1992)

The Dublin Principles further recognize that water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels; women play a central part in the provision, management, and safeguarding of water; and water has an economic value in all of its competing uses, and should be recognized as an economic good (Molden et al. 2007).

An integrated approach to water resources management is necessary and practices should be based on such sustainable water resources management principles as mentioned above. Mays (2007), for example, introduced seven requirements that have to be considered: basic water needs to maintain human health; minimum standard of water quality; basic water needs to maintain ecosystem health; long-term renewability of available water resources; accessible data on water resources for all parties; institutional schemes to resolve water conflict; and democratic water-related decision making.

Agriculture plays a key role in sustainable water resource management because it is globally the main consumer of fresh water. Although it offers significant water saving potential, agriculture is often prioritised in water allocation in order to guarantee food security. Consequently, optimized water savings in the agricultural sector as well as in the other sectors is important. Integrated water resources management is therefore indispensable in order to manage the complex set of differing water demands and uses in a sustainable way.

1.2 Black Sea Catchment

1.2.1 Black Sea Catchment

This study focuses on the Black Sea catchment. It is a catchment that covers a vast area of over two million square kilometres and comprises some of the main European river basins; the Danube in the east, as well as the Dnieper and the Don in the north. In the south, the Sakarya and Kizil Rivers constitute main river catchments in Turkey.

Map 1: Black Sea Catchment

(Source: UNEP/DEWA/GRID-Europe)

This enormous geographical extent also contains a political dimension. The Black Sea catchment includes 23 different countries. However, the extent of the country territory that is situated within the catchment area varies considerably (cf. Map 1). Countries such as Russia, the Ukraine, Turkey, or Romania cover more than 200,000 km^2, whereas other countries such as Albania, Italy or Poland cover an area of less than 1,000 km^2. Furthermore, some countries are completely or mostly located within the Black Sea catchment (e.g., Romania, Republic of Moldavia, Austria, Slovakia, and the Ukraine). In other cases, however, the country area within the Black Sea catchment is marginal compared to the total country area (e.g., Russia, Albania). Therefore, any possible country statistics have to be interpreted with caution.

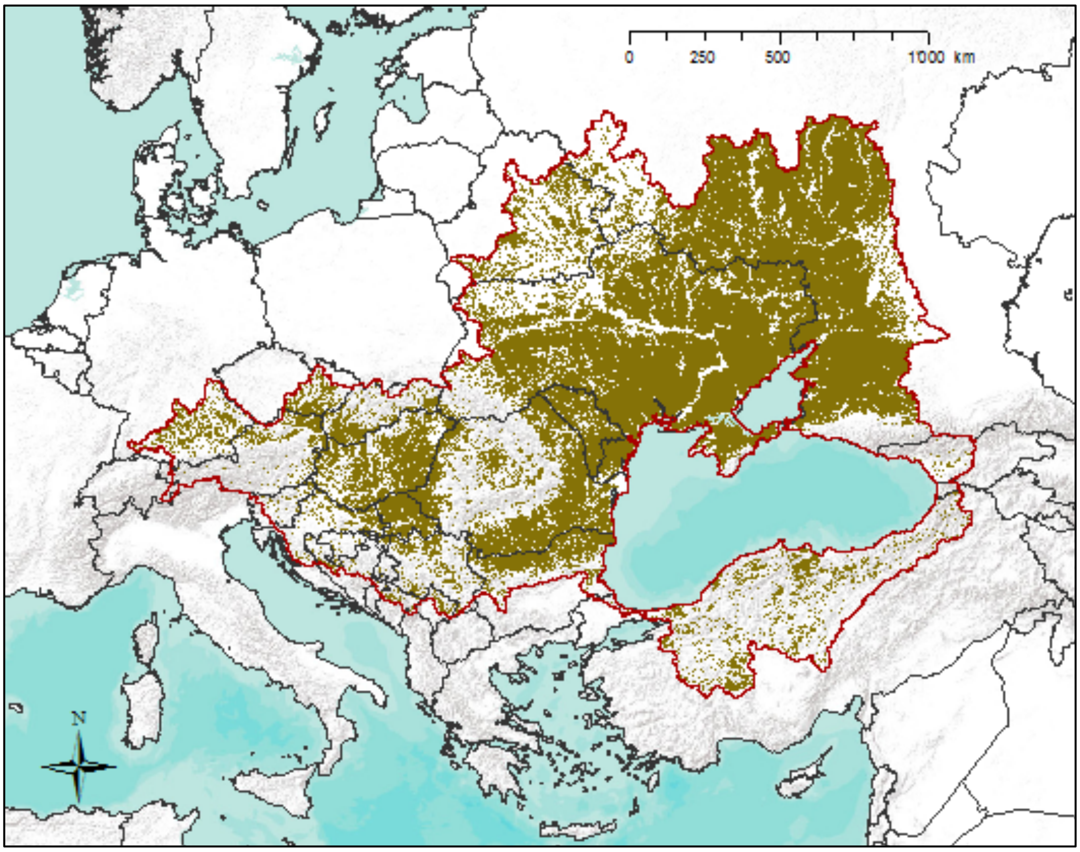
Most of the concerned countries are members of the European Union or will most likely join the Union in the future. Germany, Austria, the Czech Republic, Slovakia, Hungary, Romania, Bulgaria, Slovenia are all current members of the European Union; Croatia is an acceding country; Macedonia, Montenegro, Serbia and Turkey are candidates and Albania submitted an application. Hence, the European Union plays without doubt an important role in the Black Sea catchment.

1.2.2 Agriculture

Agriculture, in general, is important in the Black Sea catchment. Vast plant crop areas can notably be found in Hungary, Serbia, Romania, Moldavia, and especially in the Ukraine and the Russian Federation (cf. Map 2).

Correspondingly, the economic importance of agriculture should not be underestimated. The national GDP in terms of absolute figures, per capita values, sectorial composition and annual growth vary strongly between the different countries (Borysova et al. 2005) and agriculture constitutes a fundamental sector in the national economy of some countries. In 2010, for instance, the value added to the national GDP by the agricultural sector was above 10% in Belarus, Montenegro, Serbia, Macedonia, Turkey and the Ukraine. In Moldova, agriculture was responsible for almost all the national GDP. The importance of the agriculture sector is evident as well when examining the employment rates depending on this sector. In Turkey, Serbia and Romania approximately one out of four jobs are being found in the agriculture sector (cf. Annexe **Error! Reference source not found.** for more details).

Irrigation plays an important role, but in the past, irrigated areas have varied across different countries. In most of them a decline of irrigated areas has been observed in the last few decades. Since the early 1990s there has been an 88% decrease in water abstraction for irrigation in Eastern Europe, mainly due to the decline of agriculture in Bulgaria and Romania during the period of economic transition (H. Yang et al. 2011). In the remaining eastern EU countries, the total irrigable area has declined by about 20% (H. Yang et al. 2011). On the other hand, a massive increase in irrigation has been experienced in Turkey, where water abstraction for irrigation increased by 36% from the 1990 level.



Map 2: Crop Fields in the Black Sea Catchment
(Source: enviroGRIDS land use model)

Despite an overall decrease of water abstraction for irrigation, water withdrawal for agriculture remains the most important of all the types of freshwater withdrawals (cf. Figure 1) in most countries. In some countries, notably Georgia, Moldova, Turkey or the Ukraine, agricultural water withdrawal exceeds even 40% of the total freshwater withdrawals. This is of particular significance as agriculture has a high rate of water consumption through evapotranspiration. In other words, most of the water withdrawn for irrigation purposes will not be available for second use.

In the past, agricultural water stress within the Black Sea catchment was not a major issue. A lot of attention, however, has been paid from researchers and decision-makers to agricultural pollution. As one of the world's largest inland seas, the Black Sea is very vulnerable to several pressures, notably land-based pollution that causes ecosystem degradation through eutrophication (Borysova et al. 2005). The overabundant nutrients that cause this eutrophication originate approximately 80% from agriculture, 15% from urban water and 5% from other sources (Borysova et al. 2005). Thus, a catchment management approach seems most adequate to analyse and tackle such issues.

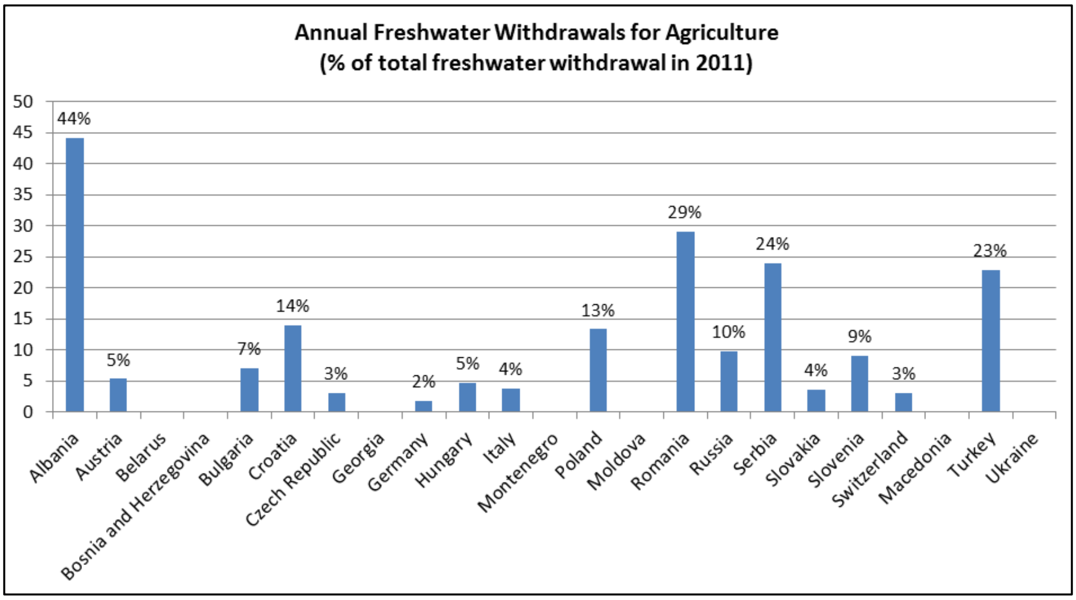


Figure 1: Annual Freshwater Withdrawal for Agriculture

(Source: FAO 2013)

In the future, the availability of fresh water resources may become major issue in the Black Sea catchment. Given that water for irrigation still consumes the most water in many countries, a climate change induced decrease of water resources is likely to lead to intensified competition for available fresh water.

1.2.3 Climate Change and its Impacts

Climate change will not spare the Black Sea region and its agriculture. As agriculture is very sensitive to climatic conditions, climate change induced alterations in temperature and precipitation will inevitably have significant impacts on the agricultural production within the catchment.

Temperature can be predicted more easily than projections for precipitation. In general, temperature is expected to increase more in winter than in summer. Furthermore, in the past an increase of warm extremes was observed as opposed to a decrease of cold extremes (IPCC 2007). For Europe an overall increase of 2 to 6.3°C is expected between 1990 and 2100 (Parry 2000). Projected trends in precipitation are more variable. In winter, most of Europe is likely to become wetter, except for the Balkans and Turkey. In summer, the north of Europe might become up to 2% wetter per decade, whereas the south might become up to 5% drier (Parry 2000; IPCC 2001).

Climate change has the potential for positive impacts on agriculture. For instance, depending on the crop types and their optimal temperatures, agriculture might benefit from higher temperatures. These optimal temperatures, however, might be exceeded as well. Flörke et al. (2012), for instance, argue that the optimal temperature for maize and sugar in the Black Sea region might be exceeded by 2050 and thus lead to decreased crop yields. Furthermore, an increase in production due to higher temperatures is only possible if the condition of possessing sufficient water resources is fulfilled.

Climate change will have a particularly strong impact on water resources. The most direct impact of higher temperatures (that lead to increased evaporation) and drier periods (that lead to fewer water provisions), is the decrease of soil moisture and thus a decrease of the water availability for plants. Consequently, it is likely that irrigation requirements in the Black Sea catchment will become substantial in some areas (IPCC 2007; M. Flörke et al. 2012; ICPDR 2012).

Increasing demand for irrigation water might consequently contribute to an increased competition for sparse water resources in a significant way. However, Flörke et al. (2012) analysed future water demand and availability in the Black Sea region and they concluded that depending on their different scenarios, water withdrawal may either increase by 58% between 2005 and 2050 or it may decrease by 59% during the same period. This illustrates the difficulty of estimating the future water demand of sectors such as industry and households if socio-economic drivers are most important. Nevertheless, scenarios used for such estimations are usually based on reasonable assumptions and such significant increases in water demand should therefore be considered as feasible scenarios of the future.

Above all, ecosystem water requirements should not be forgotten in the competition for freshwater resources between the different water sectors. Whereas some sectors can usually define their water requirements quite well and defend their interests, it is much more difficult to define an ecosystem’s water demand. As a result, water is often consumed at the expense of ecological systems’ health. The environment is in danger of being compromised, notably, by a prioritisation of the agricultural sector. In this context, the European Union Water Framework Directive (WFD) plays a crucial role in the Black Sea Catchment. This directive demands a “good ecological status” of water bodies and therefore sufficient water must be allocated to ecosystems.

In summary, agricultural water use plays a key role in sustainable water resources management in the Black Sea catchment. Agriculture is the biggest water consumer, responsible for large quantities of the total water abstraction. Consequently, it will be one of the most heavily affected sectors by climate induced water shortages due to its high water demand; it also risks to be one of the principal factors aggravating water shortages due to its high water consumption rate. Hence, understanding the spatial and temporal distribution and movement of water is crucial for efficient water resources management.

1.2.4 EnviroGRIDS Project

Facing a potential lack of freshwater resources in the future, decision-makers and stakeholders need to acquire the knowledge and information necessary to adequately coin their water management practices. The *enviroGRIDS* project addresses exactly such issues.

The project's main objectives are building the capacities of regional stakeholders to use new international standards in order to gather, store, distribute, analyse, visualise and disseminate crucial information on the past, present and future states of the environment. Consequently, this will allow for an assessment of the sustainability and vulnerability of the Black Sea catchment (enviroGRIDS 2011). Among other outputs, the project has created scenarios of demographic development, climate change, land cover changes, and hydrological models at the scale of the entire Black Sea catchment. This provides important knowledge for land-use planning and sustainable water resources management.

The here presented work is based on some of the enviroGRIDS project's outputs. A comprehensive dataset created for simulating hydrological scenarios has been used to conduct a vulnerability assessment of agricultural water resources in the context of future climate change. The obtained knowledge should enable decision-makers and stakeholders to adapt their water management policies and practices accordingly.

1.3 Vulnerability Assessment of Agricultural Water Resources

1.3.1 Vulnerability Assessment

Vulnerability, at its most basic form, is a vaguely defined term. It is derived from the Latin word vulneare, meaning "to wound" and is therefore commonly interpreted as "the capacity to be wounded" (Dow 1992) or "the potential to get harmed" (Varis et al. 2012). Apart from that, there is little consensus on the concept of vulnerability (Gain et al. 2012). Despite (or thanks to) this vague definition, the concept of vulnerability has become widely used in many different research domains and, according to Wu, Yarnal, and

Fisher (2002), it is particularly important and often applied to human-environment research (Wu et al. 2002).

The vulnerability concept has a particular importance for decision-makers and planners. Explained in a simplified way, a vulnerability assessment shows where unsustainability may be greatest and therefore where action needs to be taken. Applied to the agricultural sector, Shengcai et al. (2012) specify that the study of agricultural vulnerability in different regions "is of great significance for proactively adapting to climate change, developing effective adaptation measures and ensuring sustainable agricultural development, and also for providing a scientific basis for decision-making" (2012:2).

Hence, this vulnerability assessment attempts to offer a scientific basis for sustainable decision-making and planning related to the agricultural water resources in the Black Sea catchment. The obtained data and knowledge should make decision-makers aware of the climate change induced impacts and enable them correspondingly to develop effective adaption measures.

1.3.2 Research Questions

This study focuses on the vulnerability of agricultural water resources in the context of climate change in the Black Sea Catchment (Baer, 2013). In other words, it aims to assess the potential harmful impacts of future climate change on the agricultural water resources system. The results should enable decision-makers to adapt their management and planning strategies accordingly and therefore to make a step forward towards sustainable water resources management.

This work has two main objectives: first, designing an appropriate assessment framework; and second, conducting a vulnerability assessment of agricultural water resources within the Black Sea catchment. They can both further be subdivided into sub-objectives.

Objectives of the assessment framework:

- Clarify the meaning of the term vulnerability and explain the necessary step to assess vulnerability
- Present some important and commonly known vulnerability assessment frameworks
- Offer a conceptual framework that is context independent, i.e., universally applicable
- Apply a conceptual framework in the context of a vulnerability assessment within the Black Sea catchment

Objectives of the vulnerability assessment:

- Assess the overall vulnerability of the agricultural water resources within the context of future climate change
- Identify particularly vulnerable regions
- Decompose the vulnerability results into their components in order to explain why a region is considered to be more or less vulnerable
- Identify competing water demands
- Offer a country comparison of vulnerability results

1.3.3 Scope and Limitations

This vulnerability assessment covers all of the Black Sea catchment. Despite the vast geographical extent, the assessment will be capable of offering a comparatively high resolution, as the catchment will be subdivided in a high number of sub-basins. Nevertheless, this remains a rather crude overview. For more comprehensive and detailed information, it would be necessary to conduct the vulnerability assessment on smaller regions or even on a local scale.

The assessment will focus on agro-climatic and hydrological conditions. Agricultural policies, water management practices and the water demand of other sectors are only marginally or not at all covered. As a result, the analysis for future water resources is limited to the ecological water demand and agricultural water demand. A broader assessment would have significantly increased the interdisciplinary aspect and would have offered a much more holistic view. However, this was dependent on data availability; either no data was available or the data was only available on a national scale.

Furthermore, the assessment will not take into account different land uses. Thus, agro-climatic and hydrological conditions are analysed without taking into account whether the analysed areas are actually used for agriculture or not. Future land use changes that might increase, decrease or shift agricultural areas are therefore not included.

Further limitations of the assessment will be mentioned in Section 3.5.

1.3.4 Outline

1. Specify the vulnerability concept (Section 2.1)
2. Apply the concept to the context of the Black Sea catchment (Section 2.2)

3. Define the assessment methodology (Chapter 3)
4. Present the assessment results (Chapter 4)
5. Discuss the results in context of the Black Sea catchment (Chapter 5)
6. Conclude (Chapter 6)

2. Vulnerability in the Black Sea Catchment

2.1 Vulnerability Concept

2.1.1 Assessing Vulnerability

Assessing vulnerability, even with quantitative methods, should not be confused with measuring vulnerability. Strictly speaking, vulnerability cannot be measured "because vulnerability does not denote an observable phenomenon" (Hinkel 2011:200). Vulnerability is a theoretical concept as opposed with observable ones (e.g., heat or height). The distinction between observable and theoretical concepts has been subject to a lot of debate in the philosophy of science and there is no clear cut, because observability is a convention: if the members of a scientific discipline have agreed upon a simple and canonical way of measuring a concept, it is said to be observable (Hinkel 2011). However, as it will be highlighted in the following sub-chapter, such a uniform convention for the concept of "vulnerability" does not exist. Hence, "it is more accurate to speak about making the concept operational instead of measuring it" (Hinkel 2011:200).

The medium to operationalize a concept is a conceptual framework, which defines the elements in the system analysed and the theoretical causality-relationship among those elements. Practitioners generally agree therefore, that the first step in a vulnerability assessment must be to determine which conceptual framework of vulnerability to use and, hence, which analytical definitions of vulnerability to apply (Rygel et al. 2006).

In addition to the vulnerability concept, a second concept will be jointly used in this assessment. It is assumed here that the conjoint use of the vulnerability concept and a second well-known indicator framework can significantly increase the acceptance and comprehension of a vulnerability assessment. While a wide range of such indicator frameworks can be found in the literature (e.g., Singh et al., 2012; Juwana, Muttil, and Perera, 2012; Niemeijer and de Groot, 2008; Gaty, 2006), the DPSIR (Driver-Pressure-State-Impact-Response) framework was considered to be the most appropriate; partially due to its widespread use and acceptance among scientists and decision-makers.

2.1.2 Conceptualising Vulnerability

Vulnerability is the principal concept used in this work. However, it is a vaguely defined concept. Although the concept exists already for several decades in the context of social and environmental systems (Varis et al. 2012), it remains quite unsettled in the literature (Varis et al. 2012; Costa & Kropp 2012; Füssel 2007; Gain et al. 2012; Adger 2006). The absence of a commonly accepted definition of vulnerability makes the term broad and open to interpretation. A careful specification of the vulnerability concept is therefore fundamental, otherwise the term becomes almost useless in an interdisciplinary context (Füssel 2009).

The vulnerability concept used in this work will be based on the popular vulnerability definition specified by the Intergovernmental Panel on Climate Change (IPCC). This has the advantage that the assessment will be based on a generally well-known concept and terminology. According to the IPCC definition[3] vulnerability is determined by the degree of exposure, sensitivity, and adaptive capacity in a system (IPCC 2001). For a proper understanding, the single components of vulnerability (cf. **Figure 2**) are more precisely explained as follows.

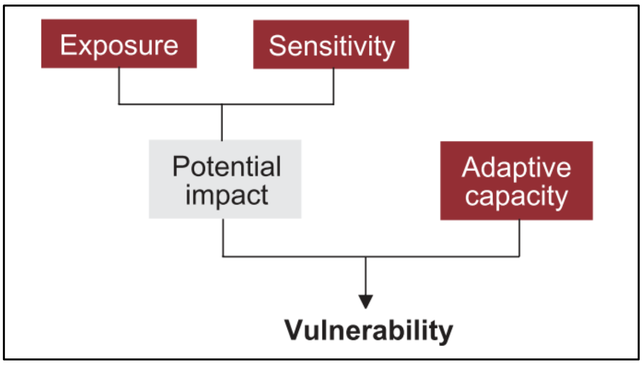


Figure 2: Vulnerability and Its Components (Allen Consulting Group 2005)

Exposure is defined as the degree or the nature to which a system is exposed to stress (IPCC 2001; Turner et al. 2003; Adger 2006). Two elements can be distinguished in this definition: on the one hand, the *unit exposed* to stress; and on the other hand, the *unit exerting stress* (stressor). Providing an illustration, the water resource, for example, would represent the unit exposed, whereas the climate condition (i.e., decreasing precipitation and increasing temperature) would be the unit exerting stress on those water resources. The former provides there-

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[3] "[Vulnerability is] the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity"(IPCC 2001).

fore the answer to the question “Who is vulnerable?” and the latter provides the answer to the question “To what is something vulnerable?”.

Sensitivity is the degree to which a system will be affected, either adversely or beneficially, by stimuli. Whereas these stimuli are defined as climate-related in the IPCC definition, stimuli can theoretically refer to any stressors previously defined. In other words, the sensitivity defines to which degree a system’s exposure to stressors can impact the actual state of the system. Climatic conditions, for example, do not impact all agricultural systems equally. Depending on the species planted, plant growth of some species and thus crop yield might depend heavily on the climatic conditions, whereas other species and thus the crop yield might be less reactive to changing climatic conditions. Sensitivity could therefore be considered as a kind of dose-response function, where the dose represents the exposure, the response the impact, and the sensitivity the function defining the relationship between the two components.

Adaptive capacity in the field of climate change is defined as “the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences’’. Adaptation is an ‘‘adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates, harms, or exploits beneficial opportunities” (IPCC 2001). For example, climate change might have less impact on crop yield if farmers have the capacity to adapt to the changing conditions (e.g., economic resources and/or groundwater availability for irrigation). It is closely linked to the question of the availability of resources (natural, economic, etc.) in order to adapt to the changes.

2.1.3 DPSIR Framework

The **DPSIR** model (Driver-Pressure-State-Impact-Response model) is the second concept used in this work. It came into use in the early 1990s when economic activities where included in environmental statistics. The model has been and is still being used by numerous international organisations (e.g., United Nations Environment Program or European Environment Agency) in order to structure environmental indicators and statistics, and to support decision-making. Furthermore, several vulnerability assessments that are at least partially based on the DPSIR framework have been conducted or proposed by scientists, and transnational and international organisations (e.g., Babel and Wahid 2008;

Bizikova et al. 2009; Huang and Cai 2009; Jun et al. 2011; UNEP 2008, 2011a 2011b; Varis, Kummu, and Salmivaara 2012).

The basic concept of the DSPIR model is the causal relationship between its elements (cf. Figure 3). It can shortly be summarised as the following: *Drivers* (social, economic, environmental) exert *Pressures* on the environment, which in turn change the *State* of the environment. As a consequence the resulting *Impacts* evoke *Responses* that can affect *Drivers*, *Pressures*, *State*, or *Impacts* likewise (Svarstad et al. 2008). A more detailed description of the DPSIR elements is presented below.

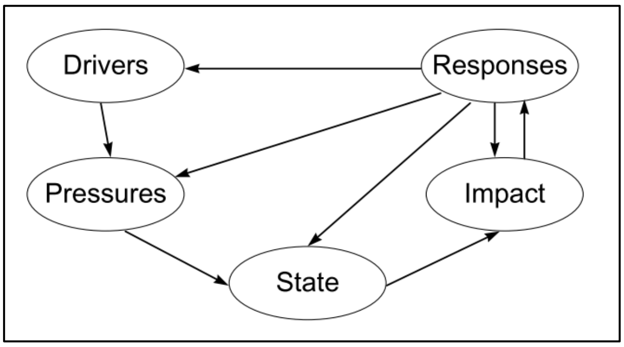

Figure 3: The DPSIR Framework for Reporting on Environmental Issues (Smeets & Weterings 1999)

Drivers are various factors that cause changes or lead the behaviour of a system as it is. Those factors can be either anthropogenic or natural (WRI 2003; Burkhard & Müller 2008). The choice of the drivers depends on the scope of the assessment. A driver could be, for example, economic development or sectorial changes. Greenhouse gas emissions could equally be defined as a driver, although they are a result of the aforementioned factors. It depends solely on how the system under examination is defined. The drivers constitute the starting point in the causal chain of the DPSIR logic and should therefore correspond to the system's definition of the assessment.

Pressure indicators are often linked to specific causes resulting from particular constellations of driving forces (e.g., land use change, climate change, etc.). Usually, pressure can be identified and measured more easily than driver indicators (Burkhard & Müller 2008). Hence, they are more easily integrated into quantitative vulnerability assessments. However, Maxim, Spangenberg, and O'Connor (2009) distinguish between different perceptions of the changes that are induced by the pressure. From a rather ecocentric point of view, any change in the environment under activity can be perceived as damaging. From a more anthropocentric point of view, however, the focus lies on the diminished benefits that humans get from the environment. Furthermore, they distinguish changes as being acceptable and incapable based on the "carrying capacity" concept. Hence, this perception should be well defined in the study as it implies inevitably normative choices.

States are the prevailing conditions. According to Maxim, Spangenberg, and O'Connor (2009), the state may refer either to natural systems alone or to both natural and socio-economic systems. Depending on the systems chosen for description, its indicators can describe "a wide range of features, from physico-chemical characteristics of ecosystems, quantity and quality of resources or 'carrying capacity', to management of fragile species and ecosystems, living conditions for humans, exposure or the effects of pressures on humans, or even larger socio-economic issues"(2009:15). States mostly result from the actions that are described as pressures (e.g., water stress, temperature stress) (Burkhard & Müller 2008). However, in this work, states that are not directly linked to pressure are considered as well. The crop type that is actually cultivated, for instance, does not uniquely depend on the pressures described. However, it describes the prevailing condition and thus affects the impacts.

Impacts result from changes in environmental states and the responses to these changes in the environment. Maxim, Spangenberg, and O'Connor (2009) note that depending on the discipline and the methodology used, the notion of impact might focus on completely different target points. In the bio-sciences an impact can refer to the effects on living beings and non-living compartments of ecosystems (e.g., aquatic, terrestrial and atmospheric) whereas in the socio-economic sciences the term focuses on effects on the human system associated with changes in environmental functions, such as resources provision, water and air quality, soil fertility, physical and mental health, social cohesion. In an agricultural related assessment impacts could equally be defined as changes in crop yields or as loss in agriculture related revenues or job opportunities.

Responses account for human actions that are taken as a consequence of any specific issues. According to Maxim, Spangenberg, and O'Connor (2009) most response indicators concern political actions of protection, mitigation, conservation or promotion and they "may seek to control driving forces or pressures (prevention, mitigation), to maintain or restore the state of the environment, to help to accommodate to Impacts (adaptation) or even deliberate 'do nothing' strategies"(2009:6). Changes in agricultural practices such as the choice of the crop type, tilling practices or irrigation could be given as an example.

The DPSIR framework might be too comprehensive in particular cases. In other cases, however, it might not be detailed enough for sufficiently depicting indicator[4]- indicandum[5] relations (Burkhard & Müller 2008). Furthermore, although such a causal chain framework enhances indicator reporting, there is much room for improvement according to Niemeijer and De Groot (2008). They recognise that such frameworks make an important contribution by emphasising the importance of causality. However, they critique that the reliance on simple uni-directional chains is at the same time not very conducive to a good understanding of the complexity of the processes behind environmental indicators.

In any case, the DPSIR framework can be used as a basis for alternative model derivations (Burkhard & Müller 2008) and improved models. Thus, most of the applications of the DPSIR model include amendments in order to adjust it to their specific needs.

2.1.4 Linking Vulnerability and the DPSIR Framework

The proposed conceptual framework for this vulnerability assessment is based on a combination of the DPSIR model and the concept of vulnerability. The goal is not to provide a thoroughgoing elaborated theoretical concept. It aims rather to provide a framework allowing the use of a common terminology. This means that the terms used in the assessment should be equally meaningful to both the scientist and the decision-maker more accustomed to the vulnerability concept, as well as to those more accustomed to the DPSIR framework. Furthermore, the framework remains generic. This means that it is not specific to a system and can thus be applied in vulnerability assessments of different research domains.

Maxim and Spangenberg (2006) offer a useful approach to reconcile the DPSIR framework and the vulnerability concept. They identify synonymous terms by systematically structuring sustainability problems and establish links between the DPSIR elements (Driver, Pressure, State, Impact, Response) and some components of the vulnerability concept (Stressors, Adaptation, etc.). Those linkages can be summarised as follows:

- The "**Driver**" category includes "**Stressors**" reflecting the latent potential of social, economic or institutional features to develop "Pressures".
- The "**Pressure**" category includes "**Stressors**" reflecting the consequences of economic activity for the environmental sphere.

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[4] indicator = the object that indicates the subject

[5] indicandum = the subject to be indicated

- The "**State**" reflects the "Inherent Vulnerability" (i.e., the biophysical structures and life support functions, which do not have a direct meaning for the social system but whose changes may indirectly lead to Impacts on humans).
- The concept of "**Impact**" has mainly the same meaning in the DPSIR and in the vulnerability vocabulary. Thus, "Impact" is a function of "Sensitivity", "Adaptation", and "Exposure".
- The "**Response**" is linked to "**Adaptation**". However, it is admitted that Responses only target the political level, while "Adaptation" (one element of vulnerability) includes more than political responses, dealing with all levels of the social, economic and institutional changes which aim at diminishing vulnerability.

These relationships will be further developed in the following section. On the one hand, they will be more adapted to the terms previously defined in this paper. On the other hand, they will adequately incorporate the aspect of “Sensitivity”. Although, "Sensitivity" is often considered a key element of vulnerability (Turner et al. 2003; Adger 2006; Miller et al. 2010), this component has not been linked to any of the DPSIR elements cited by Maxim and Spangenberg.

The modified conceptual framework links each element of the DPSIR framework (Driver, Pressure, State, Impact, Response) to a corresponding component of the vulnerability concept (Stressor, Exposure, Sensibility, Potential impact, Adaptive capacity, Vulnerability). It has to be considered that the linkage is not always a one-to-one relationship, since a term of one concept does not necessarily correspond exactly to a term of the other concept. In other words, two components of the DPSIR framework might correspond to a single component in the vulnerability concept, and vice versa (cf. Figure 4).

Stressors (vulnerability concept) are considered to correspond to the DPSIR elements of **Drivers** and **Pressures**. The drivers reflect latent changes in social, economic or environmental features (e.g. population growth, land use changes, climate change) that can cause pressure. Accordingly, pressures are human activities (e.g. waste water discharge) or natural phenomena (e.g. decline in precipitation) that are induced by the driving forces.

States in DPSIR-terms describe the prevailing conditions in a system. In our case, this signifies that states represent the system’s **Exposure** to stress as well as the prevailing **Sensitivity** of the system to this stress. In agriculture, for instance, the exposure of the system would be expressed by the actual measurable growing condition (e.g., length of growing period). Sensitivity, on the other hand, would represent the prevailing conditions that determine to which degree this exposure impacts the system (e.g., plant type and its resilience towards the stress it is exposed to). Or, in other words, sensitivity is the capacity of the environmental, socio-economic, governmental system to cope with stresses without being negatively impacted despite the fact that no specific response actions have been taken.

Impacts (DPSIR framework) are closely related to **Potential Impacts** (vulnerability concept). In both cases it is a result of changes within the state of a system. However, as the term already implies, the difference lies in the term "potential". In the DPSIR terminology the impact is the result of a causal suite of drivers, pressures and state. Response will be taken as a consequence of these impacts. In the terminology of vulnerability, however, the impact is a result of the system's exposure to stress and its sensitivity. In this case the impact remains hypothetical because it is supposed that adaptive measures could be taken before the (negative) impact occurs.

Response (DPSIR framework) is linked to **Adaptive Capacity** (vulnerability concept). Both can be seen as a reaction to specific impacts or potential impacts respectively. Responses are societal (decision-making) measures to correct the problem of the previous phases (Ness et al. 2010). Following the DPSIR logic, responses are the result of undesired impacts that already occurred. In other words, they are uniquely reactive. The Adaptive Capacity, however, is wider in its interpretation. It represents not the actual response, but the capacity to respond. Thus, adaptive measures can be taken before an undesired impact occurs. In other words, they can be preventive.

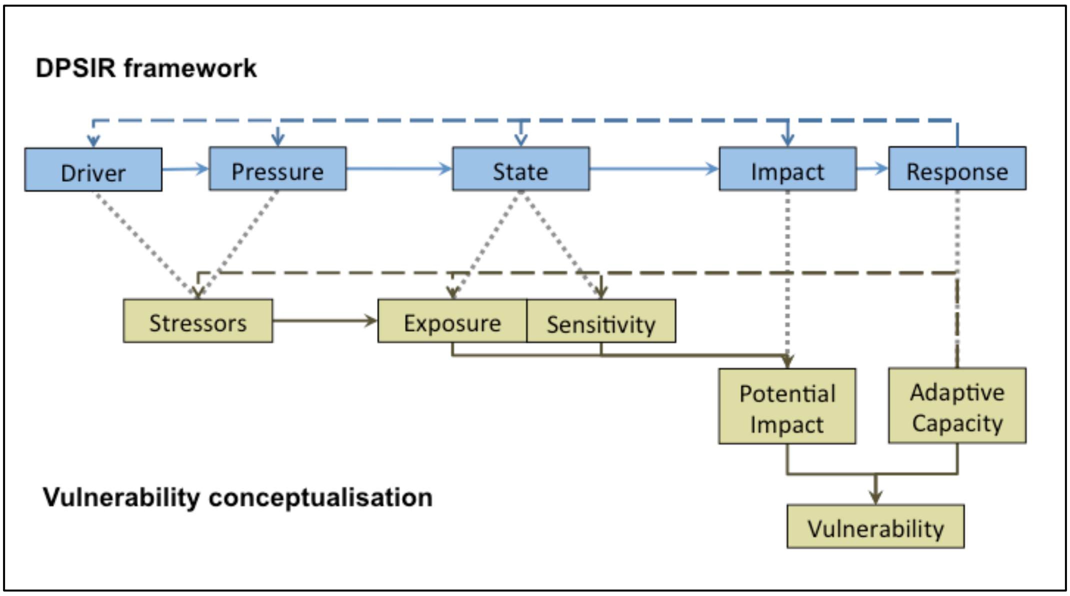

Figure 4: Linkage between the Vulnerability Concept and the DPSIR Framework

Despite these subtle differences between certain terms, we argue that linking the DPSIR framework and the vulnerability concept is feasible and beneficial. It is based on two generally well-known concepts and does not include any major modifications. Hence, it facilitates interpretation to be easily understandable to a wide range of scientist and decision-makers.

2.1.5 Operationalization

The above-presented framework constitutes a convenient groundwork for this vulnerability assessment. It clarifies the concept of vulnerability as it will be interpreted in this work and provides the related vocabulary that will be used accordingly. As Niemeijer and De Groot (2008) note, such conceptual frameworks based on causality enable clear and concise communication to decision-makers. Such frameworks, however, often have a weakness when implemented in the actual analysis process: namely, a significant discrepancy between the theoretical framework and the actual analysis process.

The theoretical framework defines the interrelation between its components (cf. dashed lines in Figure 4). Although, the DPSIR framework, for instance, is rather linear, it includes feedbacks. It takes into account the human actions that are taken in response to a specific issue (e.g., policies in order to diminish greenhouse gas emissions, extension of irrigation facilities, or change of crop types). Similarly, the vulnerability concept includes backwards interactions originating from the adaptive capacity (e.g., policy capacities in order to diminish greenhouse gas emissions, capacities for the extension of irrigation facilities, capacity for crop type change). Even though these models do not represent the reality perfectly, they usually succeed in describing some chosen processes and mechanisms in the real world.

The actual process of (quantitatively) assessing vulnerability, however, rarely incorporates such interrelations in an elaborate way. Most vulnerability assessments are based on an indicator approach that uses composite indicators or hierarchical ranking systems. Consequently, the various interactions between the different variables are not adequately comprised or may even be neglected completely.

I argue that this work will contribute to reducing this mismatch; that is, to better incorporate the interrelation between indicators, instead of evaluating the indicators as isolated variables or composite indicators. This is possible due to the fact that the assessment will be fully embedded in the SWAT (Soil and Water Assessment Tool) model and variables, thus, interact dynamically with each other. Consequently, all indicators used in this assessment correspond to a variable in the SWAT model or can, at least, be derived from it. The dynamic interrelations between the variables are therefore accurately defined and will be presented in the assessment process. The precise assessment model will be described in Chapter 3.

2.2 Contextualisation

2.2.1 Scenarios of Change

This assessment focuses on potential climatic change impacts. As explained in Section 1.2.3 the Black Sea catchment will not be spared from global climate change and, thus, significant changes in temperature and precipitation can be expected.

Projections for climate change are usually based on scenarios that describe the possible trends of the main factors driving climate change. Probably the most well-known are the greenhouse gas emission scenarios of the Intergovernmental Panel on Climate Change (IPCC). Taking this example, the scenarios are based on different assumptions about demographic development, GDP growth, energy use, land use changes, resource availability, technological developments, and societal values (IPCC 2007).

Ideally, this study would use such different scenarios and, furthermore, apply climatic downscaling. Unfortunately, both of these options were not possible. A climate model including different scenarios and a downscaling to the Black Sea catchment area was foreseen in the enviroGRIDS project. However, the results have not yet been obtained at the time of this assessment.

Therefore, the scenarios used in this study are made in a very simplified manner. They are based on two simple assumptions about the climatic developments in the Black Sea catchment as presented below:

1. **Temperature will increase by 3°C**
2. **Precipitation will decrease by 30%**

The driving forces leading to this climate change are not examined in this assessment. Furthermore, spatial variations in these changes were not taken into account. This means that changes were uniformly applied over all the catchment area.

In order to obtain different scenarios, the possibility of change in either the temperature or precipitation was considered. This allows crosscutting all those assumptions with each other in order to obtain four scenarios (cf. Table 1). The first scenario (RD) is based on a model using recorded data from the years 1996 to 2005. The second scenario (TC) assumes a temperature increase of 3°C, but no change in precipitation. The third scenario (PC) assumes a 30% decrease in precipitation, but no change in the temperature. The last scenario (CC) combines both changes, meaning that it assumes a simultaneous increase of the temperature and decrease in precipitation.

Table 1: Climate Scenarios

	No Change in Temperature	**3°C Increase in Temperature**
No Change in Precipitation	Recorded Data (RD)	Temperature Change (TC)
30% Decrease in Precipitation	Precipitation Change (PC)	Combined Change (CC)

The temporal dimension is not included in these scenarios. That means that no information about the time horizon of the climatic changes is given. This is simply due to the fact that these climatic scenarios are severely simplified and any time indication for climatic projections requires more detailed scenarios.

The here presented scenarios are nevertheless useful in the context of a vulnerability assessment. First, they allow stress (or pressure) quantification that the water resource system and agriculture might be exposed to in the future. Secondly, they allow for a distinction between the impacts caused by temperature change and the impacts caused by precipitation change.

2.2.2 Potential Impacts

Climate change might have a strong potential impact on the agricultural sectors. On the one hand, the potential impact on agricultural production depends on the frequency and the degree to which crops are exposed to climatic related stresses; on the other hand, it depends on the sensitivity of plant crops to these stresses, i.e. how likely it is that the plant will be (positively or negatively) impacted by those stresses.

Plant crops will be exposed to water stress, to temperature stress, to both, or to none. The precipitation change (PC) is the simplest scenario to estimate the potential impacts. In the PC scenario increased water stress is very likely, simply due to the fact that less water will be available.

The temperature change (TC) is more difficult to estimate. First, water stress might increase due to increased evaporation. Secondly, it is difficult to estimate the potential impact of an increase in temperature. In regions where temperatures are already high, an additional increase of 3°C might lead to stress because of temperatures that are too high for plant growth. On the other hand, a temperature increase might favour plant growth, as the plant might have suffered previously from temperatures that were too low for plant growth. Hence, whether the temperature will have a potentially positive or negative impact will depend on whether the plants already suffer frequently from temperatures that are too low or whether they already live under hot climatic conditions.

The scenario of combined change (CC) is the most difficult to estimate as it combines the potential impacts as well as the uncertainties related to the two scenarios (PC/TC). Increased plant water stress, however, remains likely and might even be intensified by the combination of the decreasing water supply and the intensified evaporation. As in the TC scenario, the potential impact of temperature change remains unclear and will depend on the current temperature condition.

The potential impact from climate change also depends on the degree of the plant's sensitivity to the new climate conditions. In other words, different plant crop types require different climatic conditions for growth. Assuming, for instance, that the minimal growth temperature is 0°C for Winter Wheat and 8°C for Maize; a temperature increase in winter would have a stronger positive impact on Winter Wheat than on Maize. Days with a temperature of 2°C instead of -1°C would become growing days for the Winter Wheat, but not for the Maize. This logic can analogously be applied to the maximum temperature and the water requirement, differing only due to fact that the temperature increase would impact more heat sensitive plants and the precipitation decrease would have more of an impact on crop plants that are sensitive to water demand.

Table 2: Expected Potential Impacts

Precipitation Change Scenario (PC)	- Increased water stress very likely
Temperature Change Scenario (TC)	- Increased water stress possible - Unknown whether increased or decreased temperature stress

Combined Change Scenario (CC)	- Increased water stress due to combination effect likely - Unknown whether increased or decreased temperature stress

This assessment, however, will not distinguish between the different crop types. This is simply because the necessary data about the spatial and temporal crop plant patterns in the Black Sea catchment was not available. A generalized set of assumptions will be applied uniformly all over the region. Therefore, the sensitivity component will not be a variable explaining spatial and temporal growth patterns.

In summary, decreasing precipitation is likely to increase water stress while the potential impact of an increased temperature is less clear since it might increase high temperature stress on the one hand, and decrease low temperature stress on the other hand. In any case, the spatial pattern of these impacts are yet unknown and will thus be examined in this work.

2.2.3 Adaption Capacity

The agricultural system has a certain capacity to adapt to climatic change and its potential impacts. Thus, in order to correctly assess the vulnerability of the agricultural sectors this variable must be included in the assessment.

An evident strategy to adapt to increased temperatures, and therefore to temperature stress, might be to change the planted crop type. As explained above, crop types have different sensitivities to (minimal and maximal) temperature stress. Hence, the adaptation capacity might be defined as the potential to change the cultivated crop type.

Such a potential would mostly depend on the high temperature stress level of the examined plant type. In the following example, two different regions are presented: in region A the major crop is Winter Wheat, whereas in region B the major crop is Maize. In both regions the planted crops are suffering from heat stress because of a recent 3°C increase of the temperature –30°C in region A and 37°C in region B. The potential for adaptation by changing the crop type would be greater in region A since the Winter Wheat could be replaced by Maize. The Maize in region B, in contrast, could hardly be replaced since its high temperature stress level is already quite high.

However, as already mentioned above, this work will not distinguish between the different crop types because the necessary data was not available. Hence, this assessment will exclusively focus on the capacity to cope with potential water stress.

Irrigation might be the most obvious adaptation strategy in order to avoid water stress. However, the future of water resources in the Black Sea catchment is uncertain and an increased competition for the available water resources is likely in the context of decreasing precipitation. This study will therefore focus on the capacity for irrigation by comparing two major water users; on the one hand, the agricultural sector and its demand for irrigation water; and on the other hand, the water bodies from which the irrigation water is withdrawn and their corresponding ecological water requirements.

Due to several reasons, water use for energy production, industry and human settlements are not included in this comparison. First, estimating future water use for these sectors is difficult and includes too many factors of uncertainty. Second, compared to the agricultural water consumption, the rates of those sectors are relatively small. These sectors are responsible for the main share of water withdrawal in some regions (FAO 2013). However, this withdrawn water is often returned to the watercourses and therefore is available for subsequent use, notably irrigation. Lastly, the water demand of those sectors is not as closely related to the climate as is the water demand for irrigation. Decreased temperature and increased temperature will almost inevitably lead to intensified irrigation. In contrast, the water demand of the other sectors is more driven by socio-economic developments.

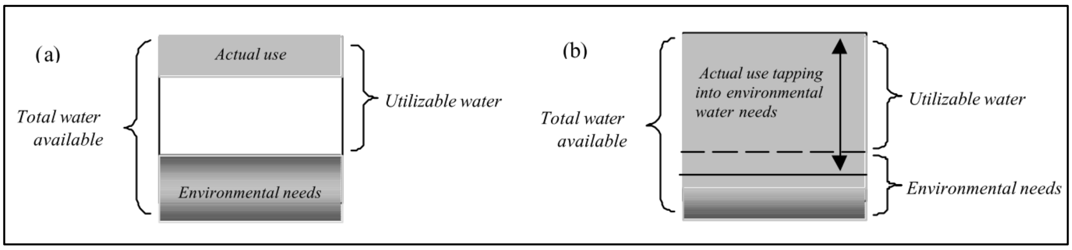

Figure 5: Relationship between available water resources, water withdrawal and environmental water requirement
(Source: Smakhtin, Revenga, and Döll 2004)

The capacity to compensate potential water stress with irrigation depends therefore mainly on whether the sources of irrigation water allow for water withdrawal or not. This assessment distinguishes two possibilities. First, water stress may be compensated with irrigation. In this case, the available water resources allow freshwater withdrawal for irrigation without compromising the environmental water requirement and thus the ecosystem's health (cf. Figure 5: a). And second, the demand for irrigation might not be satisfied due to insufficient water availability. In this case, the combined demand of environmental water and irrigation water exceeds the total amount of available water (cf. Figure 5: b). Priority will be given to the environmental requirement and irrigation will thus not be allowed.

It can be assumed that the amount of total available water and the irrigation water requirement are strongly interrelated. In other words, if the irrigation water requirement will be high, the total available water can be expected to be low; and vice versa. In contrast, the environmental water requirement will be considered static. The irrigation potential is therefore based on the differential of the available water and the irrigation water requirement, i.e., irrigation is allowed when the irrigation water demand does not exceed the amount of utilisable water.

Irrigation potential is likely to appear due to the different hydrological response times of the crop field on the one hand, and water courses, on the other hand. Lack of precipitation leads relatively immediately to water stress in most plant crops when all water from the soil has been evapotranspirated. Watercourses, however, react in a more inert and even way, since they are to a certain degree supplied by other sources (e.g., aquifers) during periods of scarce precipitation. This time lag potentially offers the possibility for irrigation.

Table 3: Expected Adaption Capacity

Any Scenario	- Some irrigation potential during water stress periods expected - Spatial distribution is unclear

Estimating the adaptation capacity is a crucial element in the vulnerability assessment. Although, the adaptation capacity in this assessment is limited to irrigation water potential, it is estimated that irrigation has a big potential to alleviate water stress. The magnitude and spatial variation of this potential, however, has yet to be assessed in this work (cf. Table 3).

2.2.4 Hypothesis

Regions where the number of plant growth days will decrease are considered as vulnerable. Accordingly, four scenarios have been created in order to assess the potential impact of climate change, to distinguish between the impact of change in precipitation and change in temperature as well as to evaluate the adaptation capacity.

Temperature increase theoretically has the potential for both, to increase the number of plant growth days or to reduce them. Which of them will prevail depends on whether the number of reduced low temperature stress days or the increase of high temperature stress days will predominate. Furthermore, higher rates of evaporation are likely to contribute to increased water stress and therefore a reduction in plant growth days. Concerning the potential for irrigation, it is likely to decrease due to higher evapotranspiration rates and consequently reduce water availability.

Precipitation is very likely to reduce the daily plant water availability. As a consequence, agricultural conditions might worsen as plant growth days might decrease significantly and the irrigation potential might decrease as less water might be available for the irrigation.

It is expected that irrigation will mitigate the impacts of the climate change, but at the same time it will be affected by the climate change. In other words, while irrigation has the potential to mitigate the impacts of reducing water resources, it is itself negatively affected by diminishing water availability.

Vulnerability, however, will depend strongly on the various interactions between different vulnerability factors that might vary considerably between different regions. Vulnerability will therefore be particularly severe where the potential plant growth days decrease and the irrigation potential increases simultaneously. In contrast, vulnerability might even increase if the natural plant growth days and the irrigation potential increase. Other cases, such as increasing irrigation potential and decreasing natural plant growth days, or vice versa, are possible as well. The big challenge is, hence, to analyse which of these factors will outweigh the others, on the one hand, and to examine how these different interaction are distributed within the Black Sea catchment on the other.

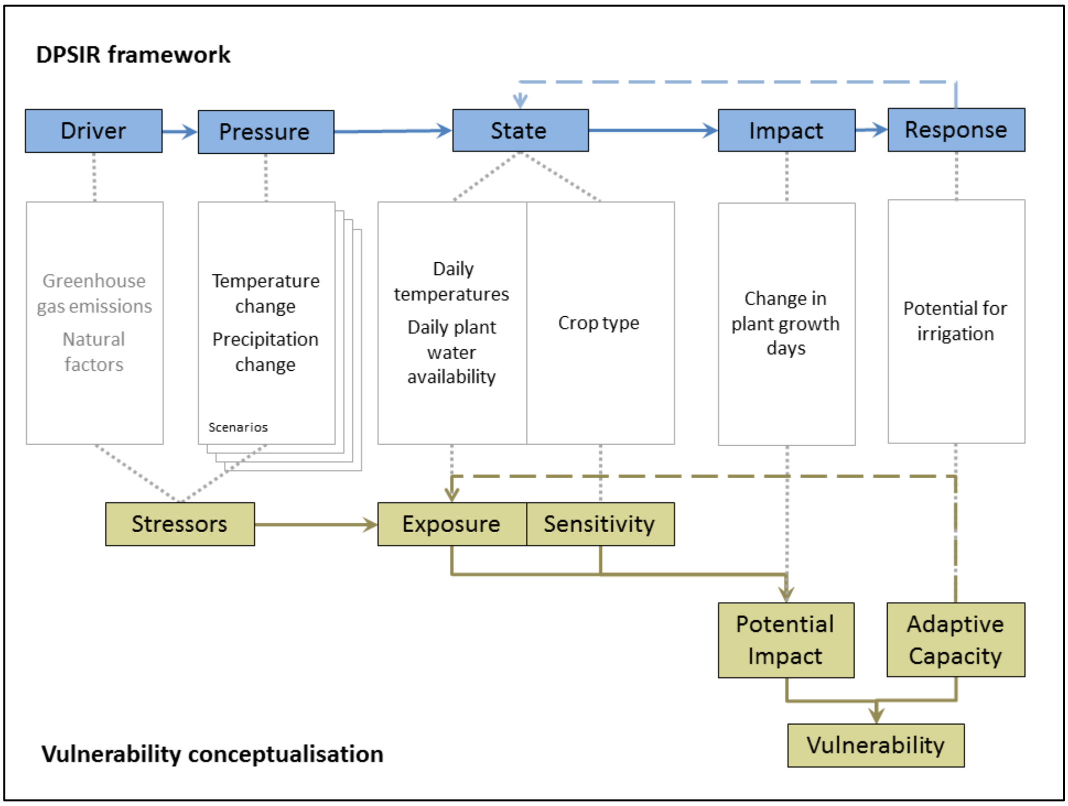

Figure 6: Conceptual Framework of the Assessment

The conceptual framework of the assessment is summarised in Figure 6. In the following Chapters, the above-presented hypothesis will be tested and we will examine the issues where no clear hypothesis could be made. Furthermore, the spatial pattern of the potential impacts and the adaptive capacity will be analysed.

3. Methodology

3.1 Assessment Model

The here presented vulnerability assessment is entirely based on the Soil and Water Assessment Tool (SWAT)[6]. It takes advantage of the vast amount of data created by the model and creates proxy-indicators that correspond to the above presented vulnerability concept and assessment framework (cf. Figure 6). It is a medium between a simulation model (e.g., SWAT) and an ordinary composite indicator framework (e.g., DPSIR) as it makes use of composite indicators, but links them in a dynamic way. The overall logic of the indicator interactions is schematically displayed in Figure 7 and described more in detail below.

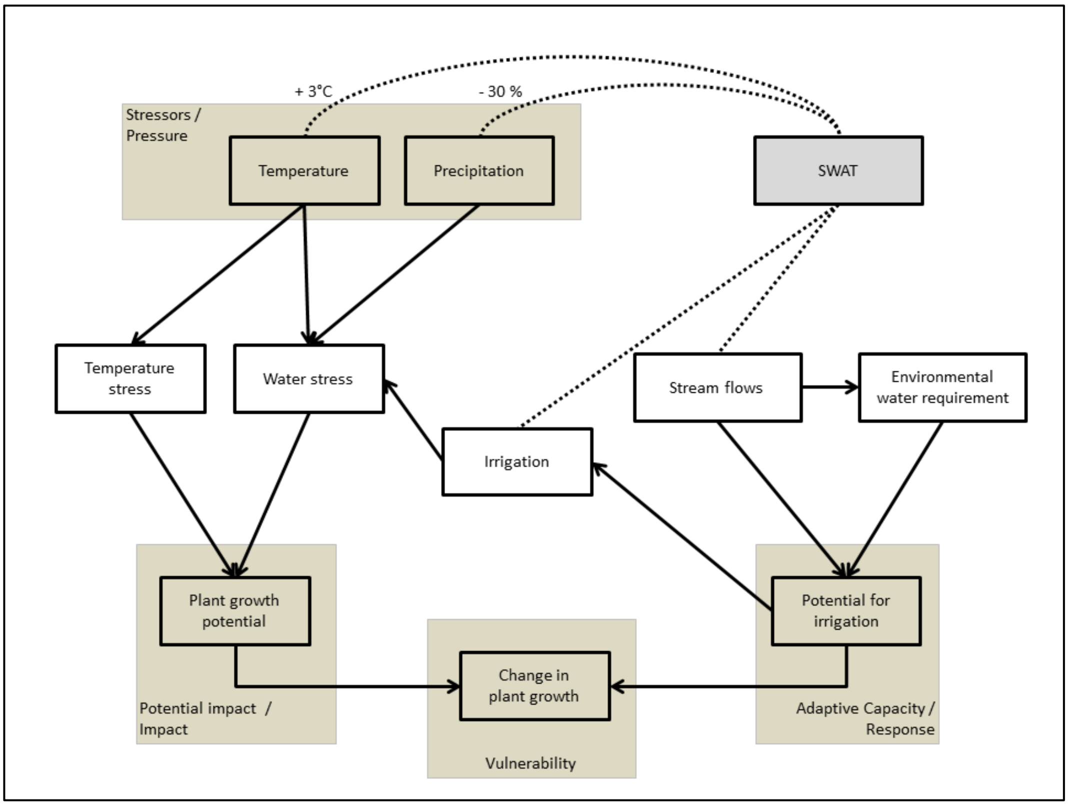

Figure 7: Schematic Overview of Assessment Model

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[6] The SWAT is explained in more detail in Section 3.4.1.

In this model, agro-climatic conditions determine natural plant growth potential. On the one hand, increasing temperatures can lead to either more suitable or less suitable temperature conditions. As a consequence, temperature stress to the plant will be either more or less frequent. On the other hand, temperature and precipitation determine the water stress of plant crops. Water stress will increase, for instance, if the temperature increases and precipitation decreases. These two factors - temperature stress and water stress - accordingly determine the natural plant growth potential.

The plant growth potential, however, does not exclusively depend on natural factors, but on human adaptation measures as well. Water stress can be reduced by irrigation. A precondition for irrigation is, however, sufficient water at its source. In this model stream flow is considered as the unique source of irrigation water. As a result, irrigation water can only be withdrawn from the river if it does not compromise the environmental water requirement.

3.2 Main Vulnerability Indicators

3.2.1 Potential Impact

The plant growth potential is used as proxy indicator for the Potential Impact (or Impact in DPSIR terms). The (natural) growth potential is defined as the annual number of plant growth days. A day is considered to be a growth day if, according to the prevailing climate conditions, the temperature and the water availability is suitable for plant growth.

In short:

> A plant day is considered to be a growth day when there is neither water stress nor temperature stress.

3.2.2 Adaptive Capacity

The potential for irrigation is used as a proxy indicator for Adaption Capacity (or Response). The irrigation potential is defined as the annual number of days where sufficient water for irrigation is available. Days with sufficient water are days where the actual stream flow satisfies the environmental water need of the watercourse (cf. Section 3.3.3).

In short:

> A potential irrigation day is considered to be a day when the actual stream flow is above the environmental water requirement.

3.2.3 Vulnerability

The expected change in plant growth is used as a proxy indicator for Vulnerability. Vulnerability is therefore defined as the change in the number of annual plant growth days. Plant growth days are days when plant growth is possible, either with or without the help of irrigation.

In short:

A change in plant growth is the change in the total number of days when plant growth – with or without the help of irrigation– is possible.

3.3 Further Model Variables

3.3.1 Temperature Stress

The number of annual temperature stress days is used as a proxy indicator of temperatures stress. A temperature range that is considered to be adequate for plant growth was defined. Accordingly, any day whose average daily temperature is below or above this range is considered to be a temperature stress day. The low temperature stress threshold was set at 5°C; the high temperature threshold at 35°C. These values have been chosen based on Porter and Semenov (2005) who consider growth below 5°C or above 35-40°C for most crops to be negligible.

In short:

A temperature stress day is as day when the average daily air temperature is below 5°C or above 35°C

3.3.2 Water Stress

The number of annual water stress days is used as a proxy indicator of water stress. Water stress is calculated as a function of the daily evapotranspiration[7] and the potential evapotranspiration[8] as proposed by Dale and Daniels (1995). Accordingly, water stress is expressed in the ratio of the actual evapotranspiration (ET) and the potential evapotran-

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[7] "Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor. It includes evaporation from the plant canopy, transpiration, sublimation and evaporation from the soil" (Neitsch et al. 2011 p.123)

[8] Potential evapotranspiration is defined by Penmann (1956) as "the amount of water transpired [...] by a short green crop, completely shading the ground, of uniform height and never short of water". The concept was redefined by other researchers suggesting to use another reference crop than the grass proposed by Penmann (Neitsch et al. 2011).

spiration (PET). The water stress threshold is set to 50%, similar to Jones et al. (2008) who define water stress days as days where the amount of precipitation and water available in the soil profile is below half of potential evapotranspiration.

In addition, a gimmick is used in order to avoid a bias in the model. The SWAT model used in this assessment applied an auto-irrigation function. That means that in regions where this function was activated water was added to the soil as soon as the plants were suffering from water stress[9] during the modelling. As a result, the irrigated plants would never suffer water stress (cf. Annexe **Error! Reference source not found.**). In order to correct this bias, the amount of water that is added by the auto-irrigation function is subtracted from the actual evapotranspiration. Thus, water stress is calculated by dividing the actual evapotranspiration (minus the added irrigation water) by the actual evapotranspiration. If this value is less than 50% of the potential evapotranspiration, water stress is occurring.

In short:

A water stress day is a day where the average daily evapotranspiration (minus irrigation water) is less than half of the potential daily evapotranspiration.

3.3.3 Environmental Water Requirement

The daily environmental water requirement is estimated in order to evaluate the irrigation potential (cf. Section 2.2.3). The indicator is based on the "natural flow paradigm" that is generally accepted concept among researchers, stating that "the full range of natural intra- and inter-annual variability of hydrological regimes is critical in sustaining native biodiversity and the integrity of aquatic ecosystems"(P. Döll et al. 2009).

The environmental water requirement of a particular day is defined as 80 % of the 10–year average runoff on that particular day. Using the SWAT model based on the recorded data, the stream flow average was calculated each day (e.g., the average stream flow for the 3rd of March is based on stream flow on that same day from the years 1996 to 2005). The threshold of 80% is based on the proposition of Chapagain et al. (2011) who propose a ± 20% range, unlike in this assessment based on a monthly mean value.

In short:

The daily environmental water requirement is estimated by calculating 80% of a 10-year average stream flow for each respective day.

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[9] It must be considered the water stress definition previously presented in this work is not the same as the definition used by the SWAT. The SWAT definition of water stress can be found in Theoretical Documentation(Neitsch et al. 2011) of SWAT.

3.4 Data

3.4.1 SWAT Model

As already mentioned above, the vast data set used in this assessment is based on a SWAT model output. SWAT is based on a basin-scale and works on a daily time step. It is developed to predict the impact of land management practices on water, sediment, chemical states and agricultural yields in large complex watersheds with varying soils, land uses, and management conditions (Yang et al., 2011).[10]

The SWAT model used in this assessment has been created in the context of the enviroGRIDS project in order to offer a comprehensive hydrological model for the entire Black Sea catchment. For the model's data preparation, the ArcSWAT toolbox (Version 2009.10.1) was used with ArcGIS 10.1.

Using the hydrological SWAT simulator, the Black Sea catchment was divided into 12,982 sub-basins, which were then further subdivided into a total of 89,202 Hydrological Response Units (HRU) that include homogeneous slope, land use, and soil characteristics. The potential evapotranspiration was calculated by using the Hargreaves method, which only requires minimum and maximum temperatures. Furthermore, an automatic irrigation function was applied because of the difficulties in obtaining irrigation schedule dates. Accordingly, irrigation water from an assumed unlimited source was applied to the concerned area when plants were suffering from water stress. Plant-nutrient deficit automatic fertilization scheduling was employed and the annual maximum application amount was set to 300 kg N/ha. Elemental nitrogen and elemental phosphorus were selected as the main fertilizer in Black Sea catchment (Rouholahnejad et al. 2013). The simulation period was from 1970 to 2006, considering 3 years as the warm-up period. Daily time step of the model was run with SWAT 2009. The model was calibrated using the SWAT-CUP calibration and uncertainty analysis package (Abbaspour et al. 2007) using discharge and NO_3 observation data in 116 monitoring points across the Catchment.

3.4.2 SWAT Inputs

The model input data were compiled from different sources. The most important are listed below:

- Digital Elevation Model (DEM): 90 meter resolution DEM v4.1 from SRTM, http://srtm.csi.cgiar.org. (Jarvis et al. 2008)

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[10] A detailed description of the model can be found in the SWAT model documentation (Neitsch et al. 2011).

- Land Use: Modis land use map with 500 meter resolution, http://lpdaac.usgs.gov (NASA 2001), maintained by the NASA Land Processes Distributed Active Archive Center (LP DAAC) at the USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. 2003. Data for the image were provided by NASA.
- Soil: Soil map obtained from the global soil map of the Food and Agriculture Organization of the United Nations (FAO 1995), which provides data for 5,000 soil types comprising two layers (0–30 cm and 30–100 cm depth) at a spatial resolution of 10 km.
- River: European Catchments and Rivers Network System (ECRINS), http://projects.eionet.europa.eu/ecrins . It is a fully connected system of watersheds, rivers, lakes, monitoring stations and dams, made from the JRC CCM2.1 and many other sources.
- Lakes: European Catchments and Rivers Network System (ECRINS), Lake data, http://projects.eionet.europa.eu/ecrins.
- Weather input data: Climate research Units (CRU), 0,5o Resolution, version TS3.0, http://www.cru.uea.ac.uk/cru/data/hrg/. (Mitchell & P. D. Jones 2005)
- River discharge: Monthly river discharge data was obtained from the Global Runoff Data Center (GRDC, http://grdc.bafg.de) for 127 hydrometric stations for the period 1970 to2006. The data was used mostly for calibration-validation of the model. Data quality check was done to choose the stations with a rather acceptable length of reliable data and minimum missing data. A few stations were also collected from the National Institutes of Romania, Bulgaria and Turkey. Overall, 79 discharge stations with relatively good data were used in the calibration process.
- NO_3 concentration: Monthly data on nitrate concentration in rivers was taken from 37 observation stations from ICPDR.
- Periods covered by the available data were from 1970 to 2006.

3.4.3 Scenarios

In this assessment, the above presented SWAT model was run four times for a time period of ten years (1996-2005). Each time, the same calibrated model was run. In order to model different climatic scenarios, however, the climatic input had to be changed before running the model.

- For the **RD scenario** no changes were made. This means that the RD scenario is based on climatic data recorded between 1996 and 2005.
- In the **TC scenario** the temperature was uniformly increased by 3°C. Spatial variations in temperature changes, however, were not considered.
- In the **PC scenario** the precipitation was uniformly decreased by 30%. Spatial variations in precipitation changes, however, were not considered.
- For the **CC scenario** the TC scenario and PC scenario were combined. That means that the temperature has uniformly been increased by 3°C, whereas the precipitation has been decreased by 30%. Again, spatial variations of those changes were not considered.

For each of these scenarios, the below presented variables were the output of SWAT. Most of them were obtained on a daily basis and on the HRU level and were later aggregated to the sub-basin level. The stream flow, however, cannot be calculated on the HRU level, and was thus obtained directly on the sub-basin level

- Total amount of precipitation falling on the HRU during time step (mm H_2O).
- Irrigation (mm H_2O). Amount of irrigation water applied to HRU during the time step.
- PET Potential evapotranspiration (mm H_2O). Potential evapotranspiration from the HRU during the time step.
- ET Actual evapotranspiration (soil evaporation and plant transpiration) from the HRU during the time step (mm H_2O).
- Average daily air temperature (°C). Average of mean daily air temperatures for a given time period.
- Average daily stream flow out of reach during time step (m^3/s).

3.5 Benefits and Limitations

3.5.1 Model

The model has the important advantage that it is dynamic. This means that it is not merely composed of independent composite indicators, but links them with each other and is thus capable of representing the interaction between the different indicators. However, compared with the possibilities that the SWAT model offers, it is a very simplified approach and thus is certainly not as precise as SWAT.

The SWAT model on which this assessment is based offers a database with unique spatial and temporal resolution for such a vast area. Thanks to the high number of sub-basins used in the model, the local impacts can be analysed, while covering the whole, extensive area of the Black Sea catchment at the same time.

3.5.2 Indicators

In general, the selected indicators represent the different components of the vulnerability concept quite well. Furthermore, they have the advantage of being calculated quite easily. Nevertheless, some principal limitations should be mentioned.

First, no variable for the vulnerability component “Sensitivity” is used. Crop plant type was foreseen as a proxy-indicator of sensitivity, but the available data on this was not sufficient to distinguish spatial differences. Thus, a generalised assumption has to be made about the plant sensitivity throughout the catchment area. This makes the sensitivity component into a constant and thus has no impact on vulnerability in this assessment.

Second, as explained above, the daily environmental water requirement is derived from a 10-year average. Mean values, however, are sensitive to extremes. To give an example: a river shows a stream flow of approximately 200 m^3/s over nine years for a particular day, but in the last year 800 m^3/s. This would result in a mean of 260 m^3/s.

And third, the irrigation potential is assessed by evaluating whether there is water available for possible irrigation. However, it does not consider the amount that is needed to compensate the water stress, nor does it take into account the amount of water for irrigation. For instance, plants in a particular region on a given day suffering from water stress theoretically require 200,000 litres of water for irrigation, while the river provides 10,000,000 litres. At the same time, there is a demand for 9,900,000 litres in order to fulfil the environmental water requirements. In this case, the model would consider the irrigation potential as sufficient since the river flow satisfies the environmental water requirement. In reality, however, water is insufficient since the river cannot provide the necessary 200,000 litres without compromising the environmental water demand.

4. Results

4.1 Potential Climate Change Impacts

4.1.1 Temperature Stress

The potential impacts of the different climate change scenarios on the number of temperature stress days are analysed in this section. In other words, we examine how the number of days per year where the temperature is inferior to 5°C or superior to 35°C develops under the different scenarios.

The overall catchment results are presented in Figure 8. It has to be considered that the following numbers represent average values of the catchment. However, the individual values for most of the sub-basins are within a range of plus or minus 31 days (standard deviation).

Under the RD scenario, the temperature conditions do not permit plant growth during 133 days because of temperature stress. In the TC scenario the number of days is 100, thus representing a significant reduction of 33 days. In this regard, it is important to distinguish the impact according the upper and lower temperature limits (35°C and 5°C). In fact, the temperature change almost exclusively affects the lower temperature limit, i.e., the temperature increase reduces the number of stress days significantly where the temperature for plant growth was previously too low. The higher temperature limit, in contrast, is exceeded only in three sub-basins (out of 12,982) during fewer than 2 days. In other words, the high temperature limit is negligible since it is virtually never exceeded, neither in the RD scenario nor in the TC scenario.

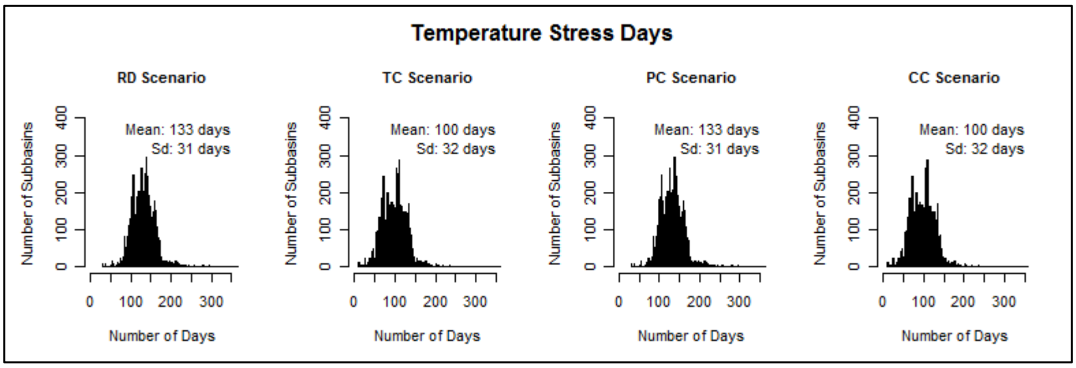
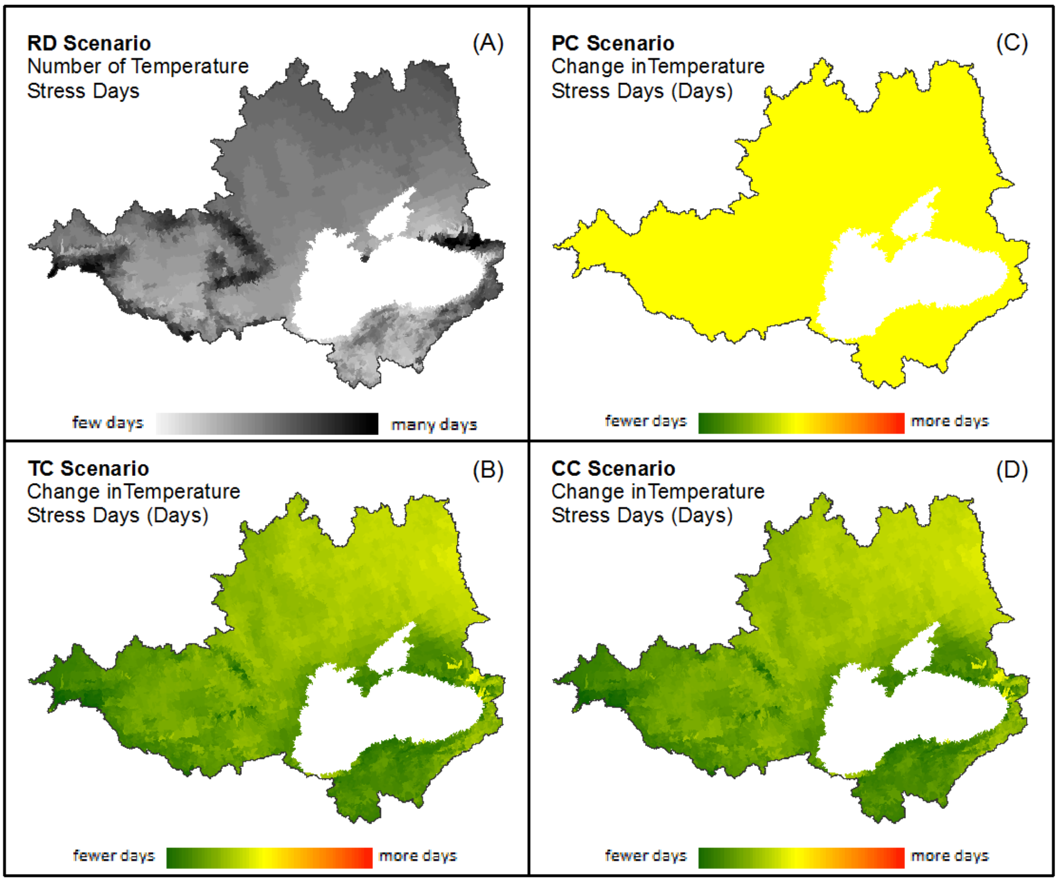


Figure 8: Potential Impact on the Number of Temperature Stress Days

Under the PC scenario no change is observed, which is obvious since the temperature has not been changed and precipitation does not influence the temperature in this model.

In contrast, the CC scenario shows the same number of temperature stress days and thus the same reduction as the TC scenario.

Temperature stress days are heterogeneously distributed in the Black Sea catchment (Map 3: A). On the one hand, temperature stress correlates positively with the altitude, i.e., temperature stress days are more frequent in high altitudes. This is simply due to the fact that the temperature naturally decreases with increasing altitudes. Furthermore, as explained above, temperature stress in the Black Sea Basin is almost exclusively caused by low temperature stress. In addition, a north-south gradient can be observed, meaning that temperature stress days are, in general, more frequent in the north than in the south.



Map 3: Spatial Distribution of Temperature Stress Days and Their Changes

The number of the temperate stress days in the RD scenario is compared with the three other scenarios. As already mentioned above, the precipitation change (PC scenario) has no impact on the temperature stress (cf. Map 3: C). Consequently, the spatial change pattern of the TC scenario and the CC scenarios are the same.

Examining (Map 3: B/D) the change follows a similar pattern as the distribution of the temperature stress in the RD scenario. Temperature stress days decrease most significantly in the mountainous regions and in the south rather than in the north.

In summary, it can be noted that the temperature increase has a positive effect on the plant growth as it reduces almost everywhere the number of days where the temperature is too low for plant growth. Furthermore, this effect is more pronounced in the south than in the north and particularly in high altitudes.

4.1.2 Water Stress

In this section, the potential impact on plant water resources is analysed for each of the different climate change scenarios. In other words, it examines the number of days where the plant crop is considered to suffer from water stress.

The numbers of water stress days per year are presented in Figure 9. It shows the catchment mean value as well as the distribution of number of days among the different sub-basins.

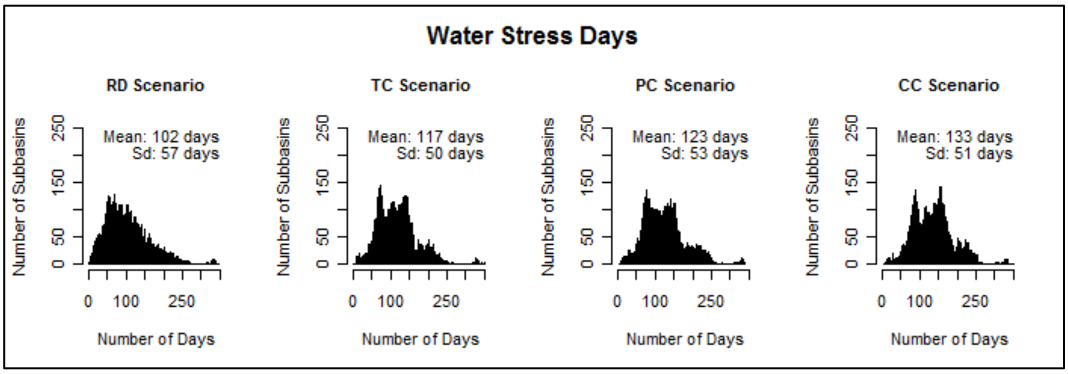


Figure 9: Potential Impact on the Number of Water Stress Days

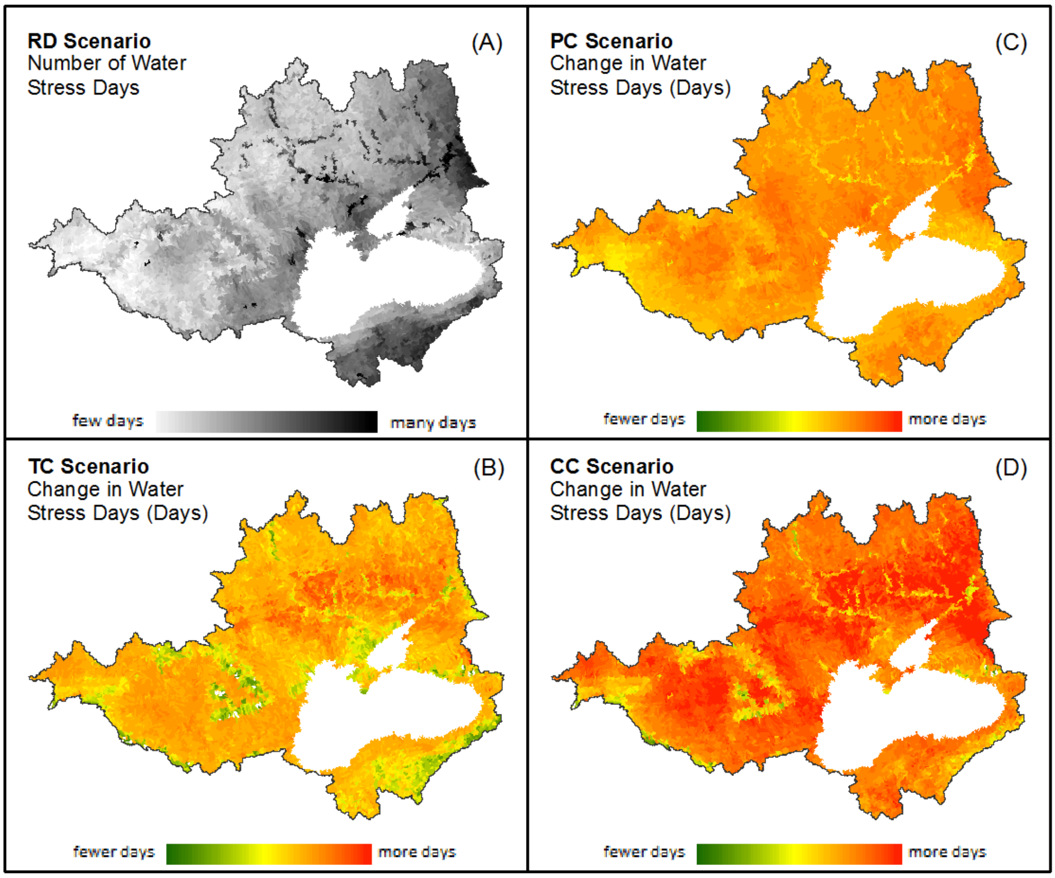
Under the RD scenario there are 102 days of water stress per year. In the TC scenario the average number of water stress day is 117, thus representing an increase in water stress days by 15 days on average. This increase is due to a higher evapotranspiration rate driven by higher temperatures. The PC scenario shows an increase of 21 days resulting in an average number of 123 days of water stress per year. This increase is exclusively due to the reduced water availability that is caused by the reduction of precipitation. The number water stress days, however, is greatest in the CC scenario. Compared to the RD scenarios the number of days increases by 31 to a total number of 133 water stress days. This significant increase is due to the combined effect of a higher evaporation rate and reduced precipitation.

In general, water stress days are more heterogeneously distributed among the Black Sea catchment than the temperature stress days (cf. Map 4: A). Water stress within the catchment is most severe in the Russian part, in most parts of Turkey and in the north of the Ukrainian peninsula Crimea. Regions with relatively few water stress days, in contrast, are found in the western part of the catchment, in the Caucasus region and in the Black Sea shore in Turkey. These regions correspond to mountainous areas, and are thus naturally more likely to experience rain.

Big spatial differences can be noted when comparing the TC scenario to the RD scenario (cf. Map 4: B). Increased water stress appears most importantly in wide areas of Russia and notably in the Ukraine. More surprisingly, however, the number of yearly water stress days decreases in some regions. This concerns mainly the mountainous areas such as the Dinaric Alps, the Carpathian Mountains, the Caucasus, or the region south of the Pontus Mountains in Turkey.

Under the PC scenario the spatial variation is considerably smaller. The regions most impacted, however, seem to be the eastern Russian part of the catchment, Ukraine and Hungary (cf. Map 4: C).

The combined impact of temperature increase and precipitation decrease (CC scenario) results in a summation and thus an increase in the water stress days in most regions. Regions in higher altitudes, however, are less affected by the CC scenario than the other regions (cf. Map 4: D).



Map 4: Spatial Distribution of Water Stress Days and Their Changes

In summary, water stress increases in all of the three climate change scenarios (TC/PC/CC). The spatial variation of this change, however, is much more pronounced in the TC scenario than in the PC scenario and can even yield a positive effect by reducing the number in water stress days in a few regions. The same applies to the CC scenario, although the increase in water stress is more pronounced.

4.1.3 Plant Growth Days

The potential number of annual plant growth days is a key variable of this vulnerability assessment. It results from the daily temperature conditions and the daily water availability. In other words, if there is neither water stress nor temperature stress the day is considered as a potential plant growth day.

The number of annual plant growth days for each scenario is presented in Figure 10. It shows the catchment's average values as well as the distribution of the number of plant growth days among the different sub-basins. Under the RD scenario the number of plant growth days is on average 141 days per year. In the TC scenario the number increases by 20 days (to 161), whereas it decreases by 12 days (to 129) under the PC scenario. When combining the temperature increase and the precipitation decrease (CC scenario) the average number of annual growth days increases by 5 days (to 146).

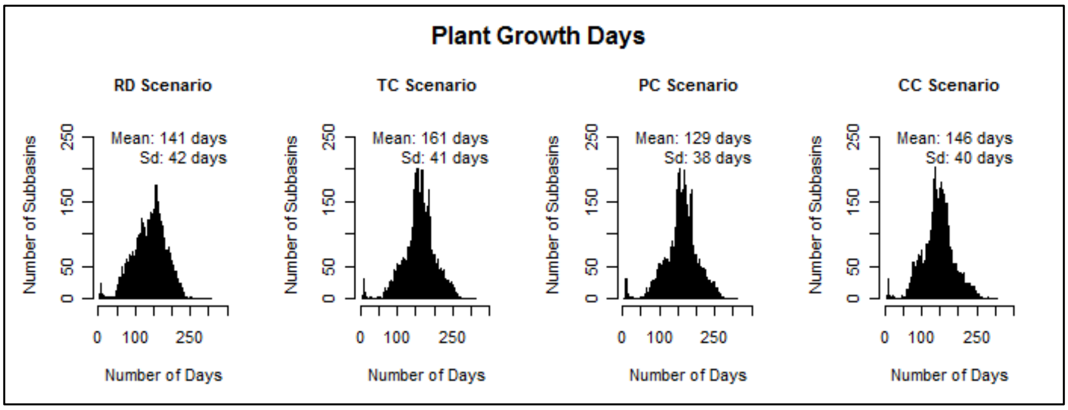


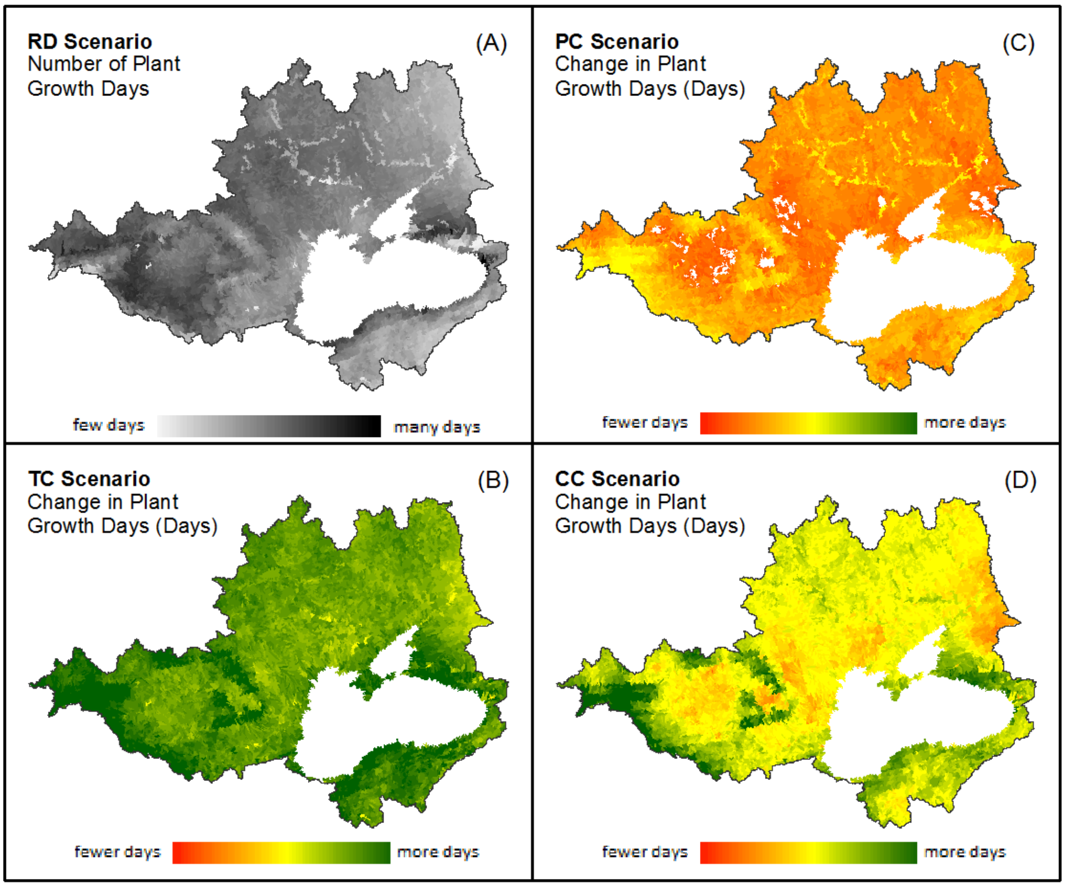
Figure 10: Potential Impact on the Number of Plant Growth Days

The above presented numbers, however, obscure the differences within the Black Sea catchment. Actually, the numbers can vary significantly when focusing on the sub-basin scale. Depending on the scenario and on the sub-basin, the number of annual plant growth days range between only 1 day and a maximum of 312 days. The spatial distribution of these variations is displayed in Map 5.

The spatial distribution of plant growth days is examined in more detail for the RD scenario (cf. Map 5: A). High numbers of days are found in wide areas in the northwest and west of the catchment as well as in the region along Black Sea shore in Turkey and Georgia, the Region between the Caucasus and the Sea of Azov. In contrast, comparatively low numbers of plant growth days are found in most of Turkey, in the northeastern part of the catchment, in the region south of the Black Sea and in the mountainous regions of the Dinaric Alps, the Alps, the Carpathians, and the Caucasus.

Under the TC scenario the quasi-totality of all Black Sea's sub-basins show an increase in plant growth days (cf. Map 5: B). This signifies that the impact of the reduced temperature stress outweighs the increased number of water stress in virtually all regions. Nevertheless, the increase is unevenly distributed in space. Regions benefiting clearly more from better climate conditions are Dinaric Alps, the Alps, the Carpathians, the Crimea peninsula, the northern half of Turkey, the region between the Caucasus Mountains and the Sea of Azov. In contrast, the regions benefiting less from increased growth days show a less clear spatial pattern. However, the region that clearly benefits the least from the TC scenarios is the east in Russia's catchment area.

As opposed to the TC scenarios, all Black Sea sub-basins demonstrate a decrease in plant growth days in the PC scenario (cf. Map 5: C). This decrease is due to the fact that the decrease in precipitation does not impact the number of temperature stress days at all (cf. 4.1.1), but significantly increases the number of water stress days (cf. 4.1.2). In general, mountainous regions are less affected by the decrease of plant growth days than the plain regions.



Map 5: Spatial Distribution of Potential Plant Growth Days and Their Changes

The CC scenario is the most interesting to examine as it directly compares and weighs the mainly positive impact of temperature increase on the one hand and the negative impact of precipitation increase on the other. Depending on the geographic location, the number of plant growth days might accordingly increase or decrease (cf. Map 5: D). Regions with clearly increasing annual plant growth days are the Dinaric Alps, the Alps, the Carpathian Mountains, the Crimea peninsula, the northern half of Turkey, the region between the Caucasus Mountains and the Sea of Azov. In contrast, regions showing a decreasing number of plant growth days are the regions in the east and in the west of the

Carpathian Mountains, the region in the northwest of the Crimea peninsula and in the most eastern part of the catchment in Russia.

In summary, the different scenarios lead to very different potential impacts. The TC scenario leads virtually everywhere to an increase in the number of potential growth days, whereas under the PC scenario the number of potential plant growth days is decreases everywhere. In the CC scenario the overall impacts for the catchment are positive, however, the changes are very heterogeneous across the Black Sea catchment. In other words, while some regions experience a very high increase in potential plant growth days, the number of plant growth days decreases in other regions.

4.2 Adaption by Irrigation

4.2.1 Irrigation Potential

The irrigation potential is the number of annual days where sufficient stream flow water is available for irrigation. In other words, water stress that occurs during those days can be remedied by the use of irrigation. As explained previously (cf. Section 3.2.2) sufficient water is available if the stream flow is above the environmental water requirement. It does not take into account, however, whether irrigation is actually needed or not on a specific day.

The results for the different scenarios are presented in Figure 11. It shows the catchment's average values for the number of potential irrigation days and the distribution of those numbers among different sub-basins within the Black Sea catchment.

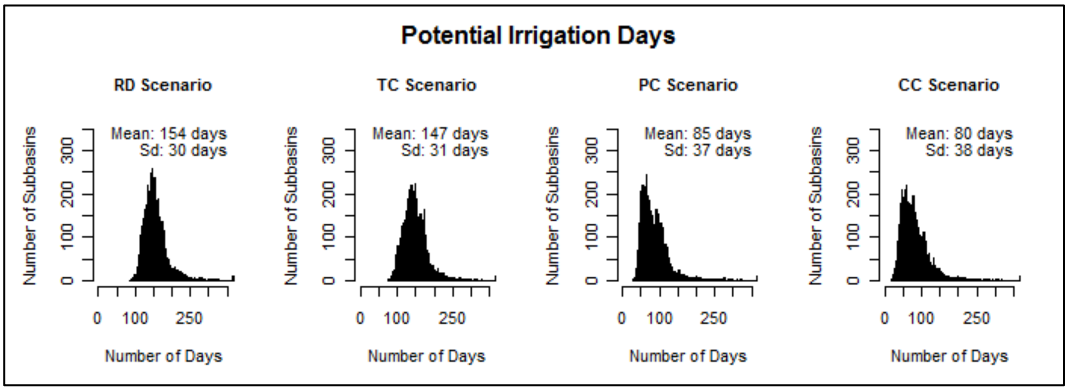


Figure 11: Potential Irrigation Capacity

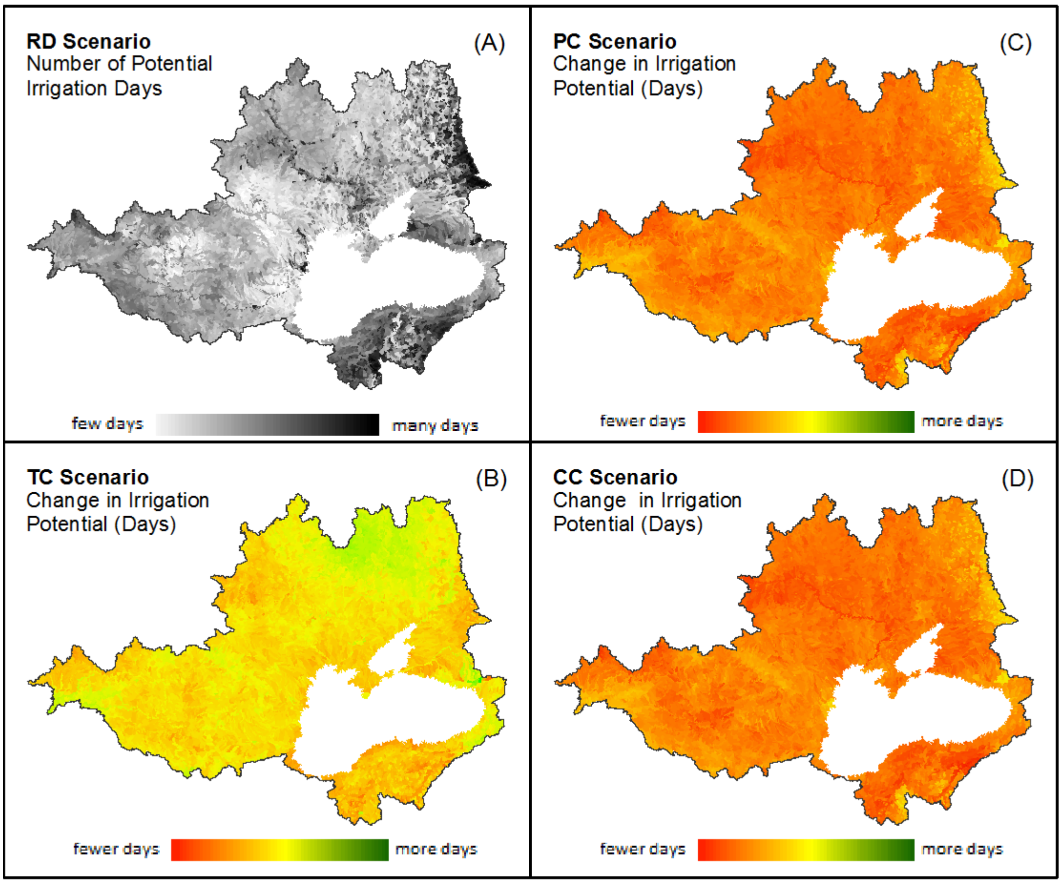
Under the RC scenario the mean number of potential irrigation days is 154 days. In the TC scenario this number decreases by 7 to 147 potential irrigation days. This decrease can be explained by an increase in evaporation and thus reduced stream flow. In comparison, the PC scenario leads to a much more severe decrease in the irrigation potential. Due to the reduced precipitation, the overall number of potential irrigation days drops by 69 to 85 days per year. Under the CC scenario the decrease in the irrigation potential is most severe. In this scenario the number of potential irrigation days drops by 74 to only 80 days per year. This sharp decrease is due to the combined effect of increasing evaporation and decreasing precipitation. Furthermore, the flattening histograms and standard deviation values in the PC and CC scenario indicate that the differences between the regions are increasing. In other words, the disparity in irrigation potential between the different regions increases in the PC and CC scenarios.

In general, the irrigation potential is more homogenous than other variables. In the RC scenario, almost all sub-basins show values between 100 and 200 days. Nevertheless, they follow a certain spatial pattern thus leading to regions with higher or lower irrigation potentials (cf. Map 6: A). The highest irrigation potentials in the Black Sea catchment are found west of the Dom River (Russia), between the Caucasus Mountains and the Sea of Azov, and in most parts of Turkey. In contrast, regions with lower irrigation potentials are found in the plains of the Danube and Dniester Rivers.

Spatial patterns in the change of irrigation potential are difficult to identify as the changes are comparatively homogenously distributed among the different regions. An interesting change, however, can be noted under the TC scenario. The northern area within Russia, the mountainous areas in the east of the catchment and the Alps show significant increases of irrigation potential. In contrast, the irrigation potentials decrease in the northeast (Ukraine and Belarus), in the south of the Russian territory, in Turkey and in German territory. No detailed explanation has been formed at this stage since it is not of major importance. However, as it will be shown later (cf. Section 4.3) this particular distribution of irrigation potential will have important implications on the agricultural vulnerability.

The PC scenario leads to quite a uniform change of irrigation potential. Nevertheless, Turkey and the northeast of the catchment are more affected by the reduction than most other regions.

The change in the irrigation potential under the CC is almost identical to the PC scenario, showing a comparatively uniform change across all of the Black Sea catchment. This is due to the fact that the reduction of precipitation has a much stronger impact on the irrigation potential than the temperature change. The heterogeneous distribution of the temperature change impacts is thus less obvious.



Map 6: Spatial Distribution of Irrigation Capacity and Its changes

In summary, the irrigation potential decreases in all of the climate change scenarios. The change in the TC scenario is unequally distributed and in some regions even leads to an increase of the irrigation potential. In contrast, the PC scenario results in a sharp and spatially uniform distribution decrease of the irrigation potential. The CC scenario results in changes similar to the PC scenario because precipitation impacts the irrigation potential stronger than the temperature change. However, the overall reduction and spatial heterogeneity of the irrigation potential is greater in the CC scenario than in the TC scenario (cf. Figure 11).

4.2.2 Additional Plant Growth Days

The adaptation capacity is measured in the annual number of additional plant growth days. These are days where plant growth is considered to be possible only with the support of irrigation. In other words, it corresponds to the number of days where, at the same time, water stress is occurring, but sufficient water is available for irrigation. It is the second key variable in this assessment.

The overall basin results are presented in Figure 12. It shows the number of additional growth days as catchment mean values as well as the distribution of the individual subbasin values.

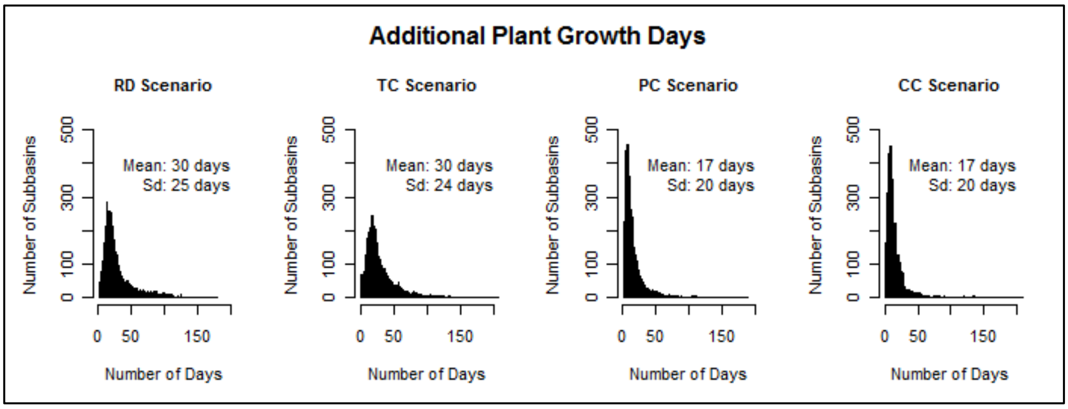


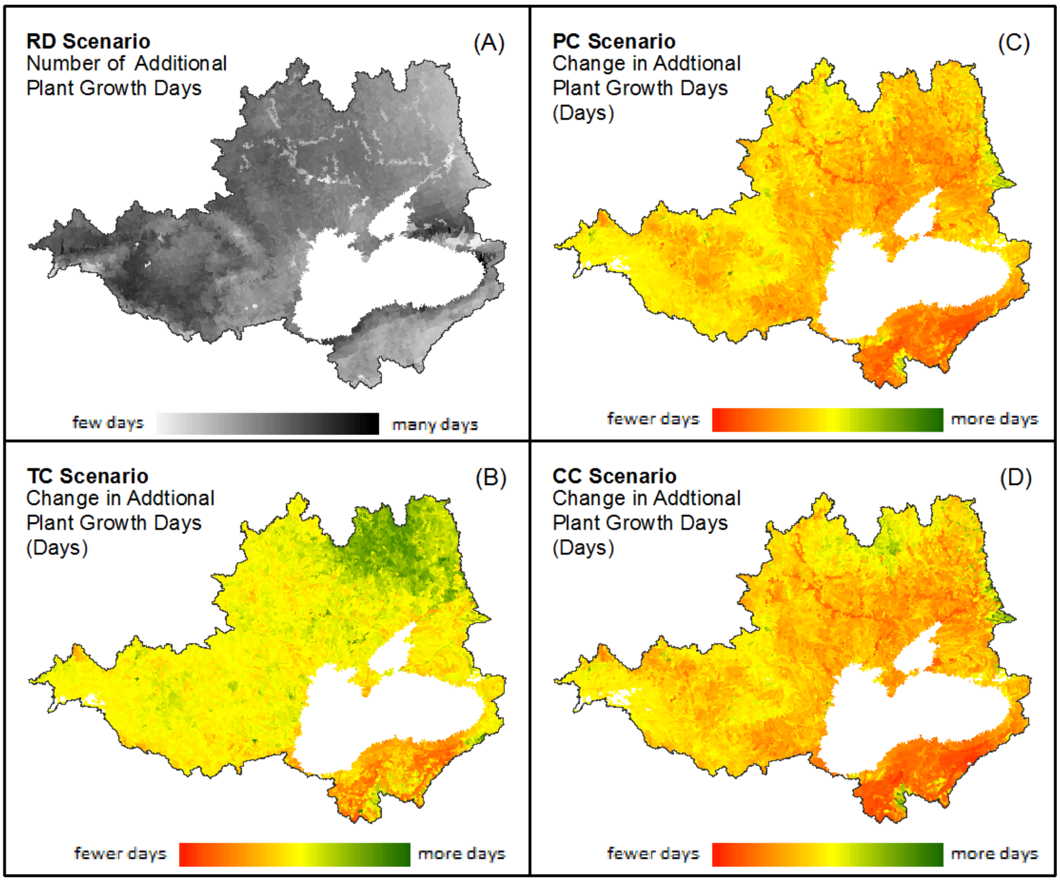
Figure 12: Potential Impact on the Number of Additional Plant Growth Days

The annual number of additional growth days is approximately 30 days in the RD scenario. Under the TC scenario the number of additional plant growth days is almost identical (30 days), while the PC scenario and the CC scenario lead to an overall reduction of the potential growth (by 13 to 17 days). However, these values should be interpreted with care since such average values can obscure significant disparities among different regions.

The additional plant growth days that can be gained by the use of irrigation are unevenly distributed within the Black Sea catchment. Examining the RD scenarios (cf. Map 7: A), a high number of days can be found in wide areas in the northwest and the west of the catchment, in the region along Black Sea shore in Turkey and Georgia, and in the region between the Caucasus and the Sea of Azov. In contrast, comparatively low numbers of plant growth days are found in most of Turkey, in the northeastern part of the catchment, in the region south of the Black Sea and in the mountainous regions of the Dinaric Alps, the Alps, the Carpathians and the Caucasus. These regions generally correspond to the regions where the annual number of plant growth days is already high (cf. Map 5: A).

In order to better understand the impact of the different climate change scenarios, their spatial patterns are examined in the following section. Under the TC scenario the main impacts can be located within two principal regions: on the one hand, the northeast of the Black Sea catchment where the number of additional plant growth days increases, and on the other hand, most of Turkey where the number of additional plant growth days decreases. The increase in the northeast is mainly due to the increased irrigation potential (cf. Map 6: B), whereas the decrease in Turkey results mainly from the decrease of the irrigation potential in this region. In all other regions changes are comparatively small and no significant spatial pattern can be observed.

Under the PC scenarios the number of additional plant growth days decreases in most regions (cf. Map 7: C). While other mountainous areas such as the Alps, the Carpathians, and the Dinaric Alp are much less or not at all affected by this decrease, the territory of Turkey is the most severely affected. In contrast, an increase in the number of additional plant growth days are rare and can only be found in isolated places.



Map 7: Spatial Distribution of Additional Plant Growth Days and Their Changes

Although the overall catchment average value for the additional plant growth days is almost equal under the PC and the CC scenarios, the spatial variations are more important in the CC scenario (cf. Map 7: D). This is result of the combined impacts caused by precipitation change and temperature change, which are both considerably variable across the Black Sea catchment. Most striking is the sharp decrease of additional plant growth days in almost all of Turkey. In contrast, in the regions at the northern and western limits of the catchment, the number of additional plant growth days increase. For the rest of the catchment, the numbers decrease in plain areas, whereas little or no change is takes place in mountainous areas. In both the PC and TC scenarios, the reduction of additional plant growth is mostly correlated with changes in water stress (cf. Map 4). In other words, whereas water stress increases in the scenario, the additional plant growth (that is due to irrigation) decreases less or even increases.

In summary, the overall number of additional plant growth days that can be gained thanks to irrigation (adaptation capacity) only decreases in the PC and CC scenarios. The spatial heterogeneity of these changes, however, is considerable. The TC shows mainly a positive impact in the north and a negative impact in the south, while the PC scenario leads to a more varied distribution with the smallest changes in mountainous areas and a very strong negative impact in most of Turkey.

4.3 Vulnerability

4.3.1 Scenario Comparison

As previously explained in this work (cf. Section 3.2.3) the proxy-indicator for vulnerability is defined as the change in the total number of plant growth days, either with or without the help of irrigation. In the following section, these days will be called "total plant growth days".

The overall catchment results are presented in Figure 13. As usual, it has to be considered that the following numbers represent the average values for all of the sub-basins. Spatial variations within the Black Sea catchment are therefore not taken into account.

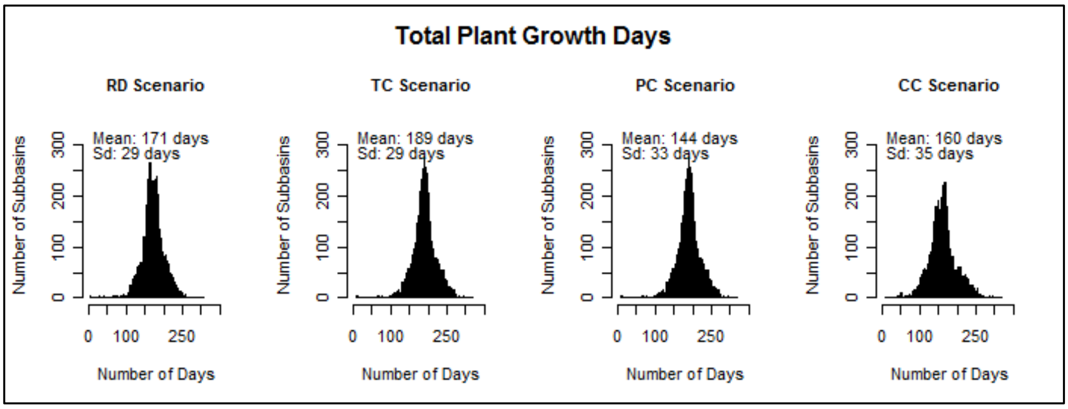
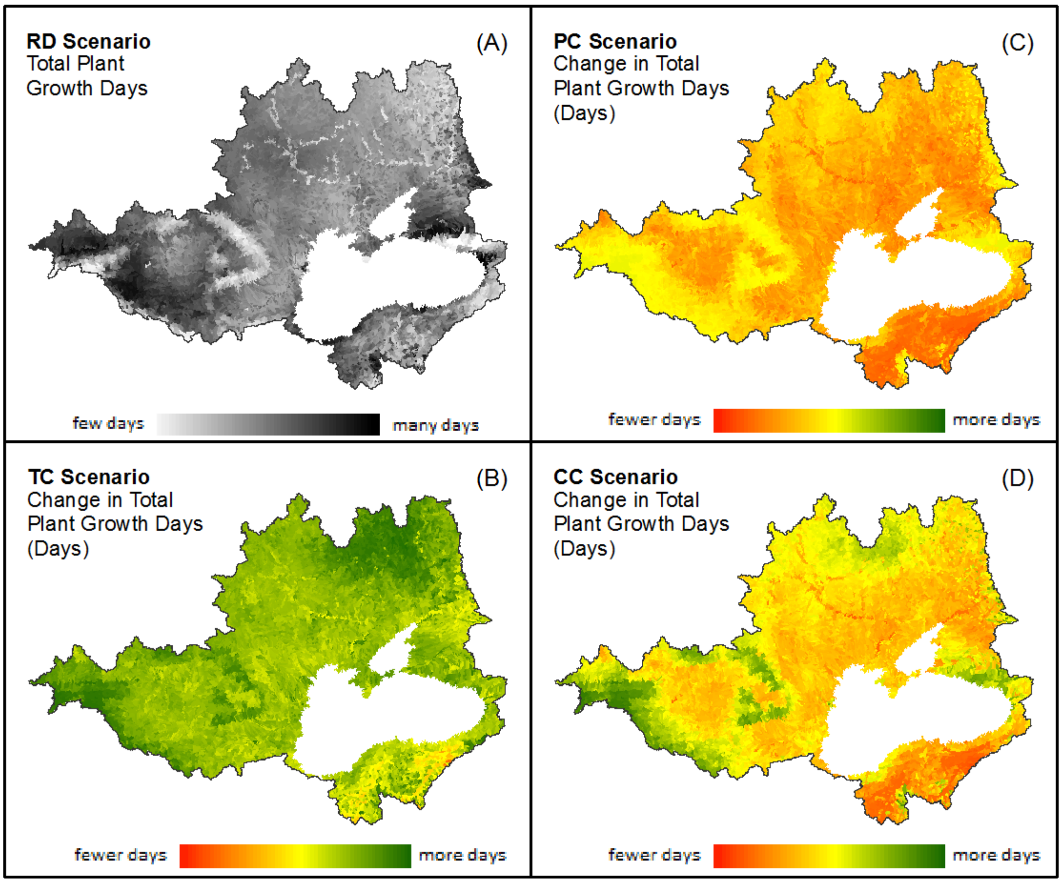


Figure 13: Potential Impact on the Number of Total Plant Growth Days

Under the RD scenario the climate conditions and the irrigation potential allow plant growth during 171 days of the year. This number increases to 189 days (+18) in the TC scenario and decreases to 144 days (-27) in the PC scenario. The increased number of plant growth days in the TC scenario is due to the more favourable climate conditions (cf. Section 4.1.3). The reduced number in the PC scenario, in contrast, is due to the combined impact of reduced (non-irrigated) growth days (cf. 4.1.3) and the reduction of the irrigation potential (cf. Section 4.2).

Under the CC scenario the total number of plant growth days decreases by 11 to 160 days per year. Although this represents a negative change, the impact is much less pronounced than in the PC scenario. However, the flattened histogram and the increased standard deviation under the CC scenario indicate a higher variance between the sub-basins than in the RD scenario. In other words, differences between the single sub-basins are increasing and certain regions might suffer particularly from the reduction of the total plant growth days, while others might be less or not at all affected.



Map 8: Spatial Distribution of Total Plant Growth Days and Their Changes

The total number of annual plant growth days is very heterogeneously distributed within the Black Sea catchment (cf. Map 8: A). In general, mountainous areas such as the Carpathians, the Alps, the Dinaric Alps, the Caucasus and the north-west of Turkey show a low number of total plant growth days. In contrast, regions with a particularly high number of growth days are situated in the plain area in Georgia, the region between the Caucasus Mountains and the Azov Sea, the eastern catchment boarder in Russia, the area in the northern Alps, and vast areas north and northeast of the Dinaric Alps.

The changes induced by the different climate change scenarios are similarly heterogeneous. The TC scenario shows increases in plant growth days (cf. Map 8: B) almost everywhere. Particularly benefiting from the temperature increase are the mountainous regions and extended areas in the north of the catchment. The increase of plant growth days in the mountains is mainly explained by the reduction of the low temperature stress days. The increase in the north, however, is due to a combination of the reduced low temperature stress and an increased irrigation potential (and thus lower water stress).

Under the PC scenario the number of plant growth days shows a somehow different spatial pattern than under the TC scenario (cf. Map 8: C). Mountainous regions such as the Caucasus, the Dinaric Alps, the Carpathians, and the Alps as well as the northwest of the catchment experience few or no changes in plant growth days. In almost all other regions, the number of plant growth days decreases. In Turkey the decrease is particularly severe. In most cases, the decrease is due to a combination of a reduced number of natural plant growth days, on the one hand, and a smaller irrigation potential, on the other hand.

Under the CC scenario the impact is most heterogeneous (cf. Map 8: D). In some regions, the number of plant growth days decreases, whereas in other regions the number of days increases significantly. The regions experiencing a positive change are the mountainous regions (Alps, Dinaric Alps, Carpathians, Caucasus,), a big area in the north of the catchment and small area in the south of Turkey. The increase in the mountainous areas is best explained by the decrease of low temperature stress days, while in the north the improvement of the growth conditions is due to the increased number of irrigation days. In contrast, the number of plant growth days severely decreases in Turkey as the number of natural growth days and the irrigation potential decrease at the same time. In the rest of the catchment the change is less pronounced, but with rather negative numbers. This reflects again the combined effect of a decrease in natural growth days and the reduction of irrigation potential that affects the majority of the Black Sea catchment.

In summary, the number of growth days increases in the TC scenario, while the number decreases in the PC scenario. The impacts are homogenous in both cases in the sense that the regions differ only in the amplitude of the impact, but not in the type (i.e., increasing plant growth days as opposed to decreasing plant growth days). The TC scenario, in contrast, results in very heterogeneous, even opposite, impacts. While some regions show a strong increase in plant growth days, the number of the annual plant growth days sharply decreases in other regions.

4.3.2 Country Comparison

In this section, the countries are compared in the CC scenario (cf. Table 4). The table first shows the total number of plant growth days per year under the RC scenario. The subsequent columns indicate the different indicators and the impact they have on the number of plant growth days (red = negative; green = positive).

The differences between the countries reflect the spatial distribution as presented above, but they are less precise since this does not take into account the differences within the country that can be considerable. The aggregation to the country level, however, can be advantageous as the results are presented probably in the most commonly used geographical unit and might therefore be more meaningful for politicians and decision-makers.

Approximately the same number of countries are benefiting from the combination of the temperature increase and precipitation decrease, as are the number of countries being rather harmed by the change. The countries benefiting most from the changes are Albania, Austria, Italy, Montenegro, Slovenia, and Switzerland. They all show considerable numbers of temperature stress days, rather small increases of water stress days or even decreases, and comparatively small reductions in potential irrigation days. It is important to note that these countries are found in mountainous areas and that these countries cover only small part of the total Black Sea catchment (cf. Map 1).

Table 4: Country Comparison

Country	Total Number or Plant Growth Days under the RD Scenario	**Change in Total Plant Growth Days (CC)**	Change in Natural Plant Growth Days (CC)	Change in Temperature Stress Days (CC)	Change in Water Stress Days (CC)	Change in Addtional Plant Growth Days (CC)	Change in Potential Irrigation Days (CC)
Albania	76.2	18.5	28.1	-44.9	-37.3	-3.0	-3.9
Austria	188.9	12.8	21.5	-39.1	29.6	-4.4	-49.7
Belarus	171.7	-7.1	7.1	-31.0	21.6	-8.9	-92.6
Bosnia Herzegovina	205.5	6.9	18.2	-36.1	33.6	-5.9	-60.3
Bulgaria	168.4	-13.5	16.8	-35.0	35.8	-16.5	-68.3
Croatia	215.3	2.7	8.1	-35.0	45.8	-4.9	-65.8
Czech Republic	182.5	-7.8	-7.3	-36.4	56.7	-9.0	-95.5
Georgia	149.4	1.3	16.6	-32.1	15.1	-9.2	-39.6
Germany	208.0	8.2	27.5	-40.0	33.1	-4.1	-74.9
Hungary	184.0	-14.1	-9.0	-34.0	61.1	-9.6	-75.0
Italy	100.8	31.4	46.6	-45.7	-19.0	-1.0	-6.5
Montenegro	136.1	14.3	29.4	-39.9	-9.9	-6.7	-32.3
Poland	169.4	7.2	15.8	-34.7	4.7	-4.8	-62.5
Moldova	168.9	-17.8	1.0	-32.5	26.1	-13.7	-71.4
Romania	166.7	-10.1	3.8	-33.9	35.0	-9.8	-67.5
Russia	158.2	-8.0	12.0	-28.8	15.3	-8.2	-64.7
Serbia	193.3	-6.6	-1.9	-34.8	54.5	-8.6	-69.6
Slovakia	176.7	-5.4	-3.9	-34.8	39.6	-8.7	-71.8
Slovenia	212.6	13.7	22.6	-36.6	27.5	-2.2	-49.3
Switzerland	61.5	39.8	57.1	-45.1	-43.4	-0.1	0.9
Macedonia	179.6	-4.4	6.4	-36.4	43.6	-6.8	-46.7
Turkey	172.9	-33.5	-1.1	-37.0	38.5	-40.7	-89.2
Ukraine	166.5	-14.3	-0.5	-31.1	33.4	-13.9	-81.5

The countries most vulnerable to CC scenario are Bulgaria, Hungary, Moldova, Romania, the Ukraine, and in particular Turkey. They all experience a decrease of 10 or more days in the number of annual plant growth days. In Turkey the decrease is even more than 33 days. The high decrease of the total plant growth days is best explained by the increase of climate change induced water stress days in combination with a particularly pronounced reduction of potential irrigation days. Other countries with high number of water stress days do show a much lower vulnerability, since the CC scenario affects their irrigation potential less. In other words, these countries would not necessarily be more vulnerable if only the natural plant growth conditions were considered (cf. Table 4). However, they are particularly vulnerable, because their irrigation potential is impaired.

5. Discussion

5.1 Opposition of Potential Impact and Adaption Capacity

The two mains components of vulnerability, as defined in this work, are potential impact and adaptive capacity. This assessment has revealed that these two components impact the vulnerability of agricultural water resources in the Black Sea catchment in an almost diametrical way.

The potential impact of climate change demonstrates a rather surprising result. In the scenario that assumes a temperature increase, the agro-climatic conditions are more favourable for agriculture than in the scenario that assumes no climate change. In contrast, the scenario that assumes a decrease in precipitation clearly shows the agro-climatic conditions worsening. In the combined scenario, the overall impact is negative because in many regions the reduced precipitation carries more weight than the increased temperature. In other words, the Black Sea catchment does not face a potentially negative impact if the positive effect of the temperature outweighs the negative impacts of the decreasing precipitation.

The adaptive capacity, however, rather shows the opposite development. The irrigation potential increases in most of the Black Sea catchment, thus contributing rather to higher vulnerability. The decreased irrigation potential is comparatively small in the TC scenario, but severely diminished in the PC and CC scenarios.

Consequently, the regions within the Black Sea catchment show very different degrees of vulnerability due to the different amplitudes of the potential impact and the adaptive capacity. While some regions are likely to benefit from the climate change, the agricultural sector in other regions is likely to be harmed. Interestingly, however, this vulnerability is mainly caused by a deteriorating adaptation capacity rather than by a worsening potential impact. In other words, climate change in most regions has a potentially positive impact on agricultural conditions, whereas the adaptive capacity diminishes in most parts.

5.2 Agreement with Other Studies

A direct comparison with other studies is difficult for two principal reasons. First, this assessment is based on the application of rather unconventional climatic scenarios (cf. Section 3.4.3), whereas most other studies use downscaled climate models. Second, most other studies either contain complex agro-climatic models or more comprehensive composite indicator assessments, while this study represents an assessment method that is in between these two approaches.

Nevertheless, the results generally correspond to the findings of other important studies. Accordingly, the reduced water availability is likely to cause increased irrigation demand (M. Flörke et al. 2012), while increasing temperatures have to potential to augment agricultural production. Although such mainly positive impacts were mostly expected in the northern regions, they were not anticipated within the overall Black Sea basin (IPCC 2007; M. Flörke et al. 2012; ICPDR 2012). Furthermore, several studies (M. Flörke et al. 2012; WWAP 2012a; Martina Flörke & Alcamo 2004) predict an increased competition for the available water resources. This assessment implies similar results, however, only the agricultural and environmental water demands were taken into account. Accordingly, the demand for irrigation water increases, whereas the water availability in the watercourses decreases at the same time. Thus, the competition for water to fulfil environmental water requirements on the one hand, and irrigation demand on the other, will increase. Lastly, similar to other studies (M. Flörke et al. 2012; Aggarwal 2009), Turkey shows a particularly high vulnerability compared to all other regions within the Black Sea catchment. The amplitude of the potential harm, however, was not expected to occur to such a great extent.

In summary, it can thus be said that the method applied in this assessment differs considerably from most other studies, but it does not reveal any significantly opposing results.

5.3 Potential for Model Improvements

The data obtained from the SWAT model proved to be exceptionally valuable. With an output that was based on 12,982 sub-basins and a daily time step, SWAT offered a database with an unprecedented high temporal and spatial resolution for the whole Black Sea catchment area.

The main weakness of this assessment may be the climate scenarios (cf. Section 2.2.1) that were utilised as no properly downscaled climate model was employed. Climate change was instead simulated by uniformly increasing the temperature and uniformly decreasing the precipitation all over the Black Sea catchment. In reality, however, climate change will be very variable across space and time (IPCC 2007). Thus, such spatial disparities and temporal fluctuations would yield considerably different results in this vulnerability assessment.

Furthermore, it should be recalled that the implemented indicators are only proxy indicators. Terms such as “number of plant growth days” or “number of water stress days” might imply that these numbers would result directly from a crop model output. However, this is not the case. The SWAT model output variables were used to create new composite indicators that serve as proxy-indicators for representing the single components of the vulnerability concept. For example, theoretically SWAT is able to model water stress and therefore the annual number of water stress days. Unfortunately, this data could not be used as the SWAT model employed in this assessment was not set up for this purpose. The use of these variables would have resulted in incorrect results. Consequently, proxy-indicators such as the ratio between actual and potential evapotranspiration (cf. Section 3.1) had to be defined for this study.

Furthermore, as already mentioned in Section 3.5.2, some of the indicators used in this assessment have a considerable potential for improvement or constitute a source of uncertainty. A lower high temperature stress limit of plants, for instance, could have led to an even higher vulnerability within Turkey. On the other hand, lower low temperature stress limits would have increased the vulnerability almost everywhere in the Black Sea catchment. Similarly, it is very likely that a redefined irrigation capacity indicator would have considerably changed the result of the adaptation capacity– whether in a positive or a negative way, however, is unclear for the moment

In summary, it can be stated that the SWAT model, as it was used in this assessment, shows a considerable potential for improvement. First, more sophisticated and realistic climate scenarios would significantly increase its acceptance within a scientific context and thus improve useful for decision-makers. Second, the choice of indicators and the definition of the threshold have a potential for improvement, but might require a more detailed investigation. Lastly, the actual SWAT output variable should be used as a vulnerability indicator. This requires that the model be specifically set up and calibrated for this purpose, but in return it would provide indicators of extraordinarily high quality.

5.4 Indicator Framework versus Simulation Model

One main objective of this work was to reduce the mismatch between the theoretical framework of a vulnerability assessment and its actual assessment method (cf. Section 2.1.5). Accordingly, the different vulnerability indicators should not be represented by independent, unrelated composite indicators, but should instead be linked with each other dynamically.

Ideally, a system is entirely modelled in order to take all essential elements of the system into account, as well as the main relationships and functions. SWAT, for instance, offers a comprehensive set of definitions that specify the elements and the definitions between them within an agricultural or hydrological system. System elements are expressed in terms of variables and constants, while mathematical formulas define the relationship between these elements.

However, modelling a system is not always possible and becomes more difficult as the system under examination becomes more comprehensive. The relationship between precipitation and stream flow, for example, is precisely defined by SWAT. The impact of different climate change induced precipitation scenarios can thus be quite well simulated.

In contrast, simulations and predictions become much more difficult and less straight forward as soon as human decision-making becomes involved. The impact of economic growth on future water use, for instance, might be positive or negative. Establishing a model with well-defined relationships thus becomes more difficult or even impossible.

Composite indicator frameworks are commonly used when the precise modelling of the interactions between the system elements is not possible. They define a conceptual framework of indicators that determines the main variables and the interaction between them. However, when evaluating the data in a qualitative way, they do not take these relationships into account, but simply aggregate system elements into meaningful composite indicators. The downside of this approach is that the interrelations that were established in theory have not been adopted in the qualitative evaluation[11]. The essential advantage of such composite indicators, however, is that they allow for much more holistic assessments. Important system elements (e.g., economic developments, demographic changes, policy practices) can be included in the assessment, although their interrelation with other variables (e.g., impact on available water resources) is not properly defined.

This assessment aimed to use only SWAT variables as indicators, thus providing a vulnerability approach that was entirely based on a dynamic model (SWAT). As a compromise, however, the analysed system had to be more narrowly defined than was initially intended. Consequently, although they are significant water users, important sectors (i.e., energy, industry, human settlements) could not be included in the assessment.

In summary, it can be concluded, that the used assessment method achieved to reduce the mismatch between the theoretical framework and actual quantitative assessment. However, in order to establish a model approach, the system had to be more narrowly defined and therefore important elements had to be omitted from this assessment.

5.5 DPSIR Framework versus the Vulnerability Concept

In this assessment, the DPSIR framework and the vulnerability concept have been combined. The aim was to provide a scheme that would allow for such an assessment in either the context of the DPSIR framework or the vulnerability concept (cf. Section 2.1.4).

Many scientists combine the DPSIR framework with their vulnerability assessments (e.g., Hamouda, Nour El-Din, and Moursy 2009; Huang and Cai 2009; Maxim and Spangenberg 2006; Omann, Stocker, and Jäger 2009; Varis, Kummu, and Salmivaara 2012). Indeed, the DPSIR framework itself does not define vulnerability. Linking these two concepts therefore contributes to a better understanding of each of them and how their components are linked to one another.

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[11] In Section 2.1.5 this phenomenon was referred to as the mismatch between the theoretical frameworks of a vulnerability assessment and its actual assessment method.

It has become evident, however, that the IPCC's (2001) definition of the vulnerability concept is more adequate for vulnerability assessments than the DPSIR framework. The simplest explanation for this is that the IPCC definition provides a definition of vulnerability, whereas vulnerability in the DPSIR framework has yet to be defined. Additionally, the vulnerability concept offers components that allow for an aggregation of the assessment variables into meaningful categories. Therefore, using the DPSIR framework in order to group single variables into composite indicators becomes unnecessary.

In summary, the proposed combination of the DPSIR framework and the vulnerability concept offers a solid approach. It is, however, concluded that the use of only the vulnerability concept is more convenient than employing the DPSIR framework or a combination of these two concepts.

6. Conclusion

6.1 Main Results

This work has conducted a vulnerability assessment of agricultural water resources within the Black Sea catchment. Agricultural water resources play a key role in sustainable water resources management since agricultural water use has the highest water consumption rate of all sectors. Furthermore, agriculture is likely to be the sector that is most severely impacted by future climate change. This vulnerability assessment has therefore aimed to design an assessment framework that is adapted to the context of the Black Sea catchment's agricultural water resources and to conduct a corresponding vulnerability assessment in order to identify potential future harm.

The vulnerability assessment has revealed that the different regions in Black Sea catchment are likely to be impacted by climate change very differently. Some countries might benefit from climate change, while others might encounter worse agro-climatic conditions in future. Notably, most mountainous areas are likely to benefit from climate change. An exception, however, is Turkey, which is likely to be most severely harmed by future climate change.

Lastly, this assessment was able to distinguish different components that cause vulnerability. Interestingly, the climate change scenarios did not deteriorate the initial natural plant growth conditions, but actually improved them in many places. Higher vulnerability was rather the result of reduced available water resources in rivers which consequently led to an increased conflict between irrigation water demand and environmental water requirements. The irrigation potential thus decreased significantly since, in this study, the environmental water requirement was given priority over the irrigation water demand.

6.2 Policy Implications

Such scenarios will without doubt constitute a major challenge for sustainable water resources management in the Black Sea catchment. Competition for the available water resources is likely to become further aggravated if other sectors (i.e., human settlements, industry and energy) display increasing water demand in the future. Hence, a sound legal framework is important. The European Water Framework Directive therefore plays a crucial role since this legal text applies for most of the countries within Black Sea catchment or will do so in the future.

Furthermore, more effective and sustainable agronomic practices can help to alleviate potential negative impacts. Deficit irrigation[12] (Fereres & Soriano 2007), the use of less water intensive crops (EEA 2010; TERI 2009), waste water irrigation options (TERI 2009), and shifting to modern pressurized irrigation systems (aus der Beek et al. 2011) are only a few such practices to be mentioned. The benefits of these practices are twofold. They reduce the water demand and consequently the vulnerability of the agricultural sector. Additionally, they also contribute to a reduction in water consumption and therefore alleviate competition for available water resources.

6.3 Scope for Further Research

This vulnerability assessment is only a first step to a better understanding of agro-climatic and hydrological processes within the Black Sea catchment. The SWAT model offered by the enviroGRIDS project hereunto provides a unique database for further research.

First and foremost, a downscaled climate model could significantly increase the plausibility of the climate scenarios[13]. A vulnerability assessment based on this improved database would offer new findings closer to the reality.

Secondly, the assessment could be extended to other sectors (i.e., human settlements, industry and energy). As aforementioned, this presents a challenge since modelling the water use of these sectors is difficult and less reliable. However, it would essentially contribute to a more holistic view.

In this context, it might be interesting see to how the SWAT model could be expanded or coupled with economic, social and policy-making models. Vulnerability assessments should aim to abandon the use of mere composite indicator systems and orient themselves towards more dynamic models. For this, however, there is still a long way to go.

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[12] Deficit irrigation is defined as the application of water below full crop-water requirements (evapotranspiration) and is considered as an important tool to achieve the goal of reducing irrigation water use. (Fereres & Soriano 2007)

[13] A down scaled climatic model for the Black Sea catchment should have been prepared in the enviroGRIDS project and should be available by now

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