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Integrating Climate Change into a Conceptual Framework for River Basin Management by the Example of the Rhône River Basin

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **MAG. JULIA CHRISTINA KOSTAL, B.A.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "INTEGRATING CLIMATE CHANGE INTO A CONCEPTUAL FRAMEWORK FOR RIVER BASIN MANAGEMENT BY THE EXAMPLE OF THE RHÔNE RIVER BASIN", 78 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 13.06.2019

Signature

Abstract

With the adoption of the European Water Framework Directive in 2000 European Member States have set ambitious goals for River Basin Management (RBM) to be reached in 2027. However, European rivers, indispensable for human life and irreplaceable hubs for freshwater ecosystems, are strongly impacted by existing anthropogenic pressures and highly sensitive to alterations of the hydrologic cycle induced by climate change. As, with global warming and human water use, multiple stressors impact water quantity and water quality, conserving and restoring good ecological and chemical status of rivers particularly in climate-sensitive regions such as the Rhône River Basin, has become a herculean task for water management.

By modifying the conceptual model "Driver-Pressure-State-Impact-Response" (DPSIR), this thesis aims to show how climate change directly influences anthropogenic activities and natural conditions, thereby producing consequences for human water use and the ecological and chemical status of surface water bodies.

Previous modifications of the DPSIR framework and policy responses towards integrating climate change into RBM guide the development of the "Driver-Pressure-State-Impact-Response-Climate Change" (DPSIR-CC) model. By the example of water management in the Durance catchment, a sub-catchment of the Rhône River Basin, the case study illustrates how climate projections and hydrologic models could inform water quality management. A qualitative to semi-quantitative analysis allows assessing how changes in the water environment could affect hydropower production and how ecological and chemical status of the Durance River could be impacted. Results obtained within the case study show that the model is suitable for water quality monitoring, since it allows analysing the interrelation between various causes which trigger changes in the environment. The case study, however, revealed a lack of consistent terminology, a weakness, which results from adopting the precursor model without establishing a novel definition for each component. Furthermore, it was found that additional research on climate change impacts on rivers and streams is needed in order to build a thorough understanding of emerging challenges for River Basin Management. Finally, this thesis has developed a structure, which allows water management tackling the herculean task of integrating climate change into a conceptual framework for water quality monitoring.

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List of Abbreviations

BDI	Biological Diatom Index
BQE	Biological Quality Elements
CIS	Common Implementation Strategy
CO_2	Carbon Dioxide
DPSIR	Driver-Pressure-State-Impact-Response
DPSIR-CC	Driver Pressure State Impact Response-Climate Change
EC	European Commission
EDF	Électricité de France
EEA	European Environment Agency
EQS	Environmental Quality Standards
EQSD	Environmental Quality Standards Directive
EU	European Union
GEP	Good Ecological Potential
GHG	Greenhouse Gas
HMWB	Heavily Modified Water Bodies
IPCC	Intergovernmental Panel on Climate Change
MSFD	Marine Strategy Framework Directive
MW	Megawatt
PoM	Programme of Measures
RBD	River Basin District
RCPs	Representative Concentration Pathways
RBM	River Basin Management
RBMP	River Basin Management Plan
WFD	Water Framework Directive

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1. Introduction and Problem Statement

Almost twenty years after the adoption of the European Union (EU) Water Framework Directive (WFD; Directive 2000/60/EC) the EU Commissioner for Maritime Affairs and Fisheries states that “there is good news”, since the “declining trend of water quality has been reversed” (EC 2018). However, the latest report of the European Environment Agency (EEA) reveals that over 60% of surface water bodies have not yet reached good chemical and good ecological status or potential (EEA 2018a, 6). While more than 70% of groundwater bodies have achieved good chemical and good quantitative status in 2019, hydro-morphological alterations and diffuse source pollution strongly impact the water quality status of surface water bodies (ibid). Despite severely influencing freshwaters, climate change is not explicitly mentioned in the WFD. Unprecedented changes in water quality and quantity have hence created additional challenges for achieving the goals of the WFD. The report of the EEA *Climate Change Impacts and Vulnerability in Europe 2012: An Indicator-Based Report* describes the following climate change effects on freshwater systems based on projections, which indicate that temperatures could increase over 2°C until 2100 compared to the pre-industrial average (EEA 2012). Particularly southern and eastern Europe could experience significant reductions in river flow, more frequently occurring extreme precipitation causing floods in northern European regions could create socio-economic losses and exacerbate existing pressures on water resources. Agriculture and forestry, climate sensitive sectors, could feel the strongest impact from extreme weather events. Sea level rise, ocean acidification, and changes in rainfall patterns could severely affect fishery. Infrastructure and buildings could be impacted by extreme events, coastal zones being the most vulnerable areas. The reduction of river flows could limit the dilution capacity, causing the concentration of pollutants to rise, while extreme precipitation could produce floods, which mobilise toxic substances. Coupled with the effects of climate change, urbanisation and population growth could pose serious challenges to wastewater treatment infrastructures. With more frequently occurring low flow regimes, particularly in summer, energy production, namely nuclear power and hydropower, could experience a decrease in efficiency. Peak seasons in tourism during low flow regimes in summer could create conflicts in water use at the prospect of rising water demand for agricultural irrigation (EEA 2012, 19ff). An overall decrease in precipitation and surging near surface temperatures are expected to severely affect regions, where water resources are already scarce (Kovats et al. 2014, 1275). Accordingly, river basins located in Mediterranean climate are “water related vulnerability […] “hot spots”, where climate change impacts on freshwater resources in the decades to come are a threat to the pursuit of sustainable development of the affected regions” (Kundzewicz 2008, 3).

In the Rhône River Basin, located in the south-east of France, far more than one third of the sub-catchments have been experiencing water shortages and unprecedented changes in climate conditions have been identified as potential threat to achieving the WFD’s objectives (Le Comité de Bassin Rhône-Méditerranée 2015, 35). Due to its highly diverse climate, geology, and land-use patterns, water resources in the Rhône River Basin are highly vulnerable to changes in temperature and rainfall. Particularly rivers originating in alpine areas and traversing several different geological and climatic regions are projected to be strongly affected by climate change induced alterations of the environment. Shrinking winter snowpack at its source and summer droughts in downstream catchment areas occurring at periods of peak demand for human water use, strongly affect the southern sub-catchment of the Durance River. As a result, cumulative effects from several pressures could have severe implications for the aquatic ecosystem.

Since the Durance River is subject to multiple anthropogenic pressures, climate change induced alterations in amount and seasonality of river runoff could create constraints for human water uses and negative consequences for the ecological and chemical status of surface water bodies. In the south-east of France, electricity production from hydropower plays a crucial role in supplementing thermal power plants. While climate change mitigation policies boost the generation of renewable energy, namely hydropower[1], a projected reduction and temporal changes of flow regimes in southern European streams could impact their efficiency (Behrens et al. 2017).

Hydro-morphological changes and water abstraction, resulting from multiple anthropogenic activities, have strongly altered the natural flow of the Durance River. Artificial reservoirs for hydropower generation and agricultural irrigation networks have been the main reasons for the failure to achieve good ecological and chemical status in a large section of the Durance River (eaufrance 2015).

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[1] The International Energy Agency (IEA) forecasts that “hydropower remains the largest renewable electricity source by 2023” (IEA 2018).

In the Mediterranean river catchment, where water shortages are expected to occur more frequently, existing anthropogenic pressures are already impacting water quality and quantity. Hence, RBM is facing unprecedented challenges. To deal with multiple existing and potential future impacts on rivers, water management needs to develop robust measures informed by long-term climate projections.

Existing water quality monitoring tools established within the Common Implementation Strategy (CIS) of the WFD provide a conceptual framework to describe how anthropogenic pressures trigger changes in water bodies. This thesis assumes that existing approaches should be adapted in order to build a thorough understanding of the connection between projected changes of atmospheric temperatures, resulting impacts on waters, and anthropogenic pressures on the aquatic environment. To address emerging challenges, this thesis works with the “step-by-step and cyclical” (EC 2009, 2) monitoring tool, established within the WFD, since its simple structure “makes it well suited to adaptively manage climate change impacts” (ibid).

Considering that by 2027 all European surface water bodies should have reached good chemical and ecological status, this thesis stresses the need and the urgency to develop a conceptual framework towards managing the complex interaction of multiple pressures on water resources. Notwithstanding the limitation of the analysis to surface water bodies, this thesis aims to develop a model suitable for the management of groundwater bodies in a similar way.

Guided by the following questions, the author first analyses existing monitoring approaches and second puts the subsequently created model to test by applying it to a specific example.

1.1. Research Questions

The thesis is structured into two parts. First, the theoretical part develops a model, which, subsequently will be put to test in the second part, a case study on the Durance River catchment, a sub-catchment of the Rhône River Basin District “Rhône Méditerranée Corse” in France.

Part one analyses how climate change could be integrated into a conceptual approach to evaluate the anthropogenic and the environmental impacts of climate change based on the following question.

1. How could the implications of climate change on anthropogenic water uses and water quality status be described within one structural approach?
   Does the Driver-Pressure-State-Impact-Response (DPSIR) model offer a framework to integrate climate change into RBM?

Question 1 highlights the need to address challenges global warming potentially creates for human water use and for the environment at the same time.

Part two consists of a case study to evaluate the functioning of the model developed in part one. This part addresses the following questions:

2. How could climate change affect anthropogenic and natural factors, which influence the components of the state of surface water bodies?
3. Which consequences for anthropogenic water uses could arise thereof?
4. Considering the results from question 2, how could the current water quality status change and thereby influence the achievement of the WFD’s goals?

Overall, the answers to question 2 to 4 intend to give an overview of the most pressing issues potentially relevant to achieving the WFD’s objectives.

2. Materials and Methods

This chapter explains the methodology applied to address question 1 to 4 and describes the research materials used.

2.1. Theoretical Part: Development of the DPSIR-CC Model

The first part of this thesis develops a conceptual framework, which integrates climate change into an existing tool for water management. The answer to question 1 provides the structural framework for addressing questions 2 to 4 in the case study.

2.1.1. Methodological approach

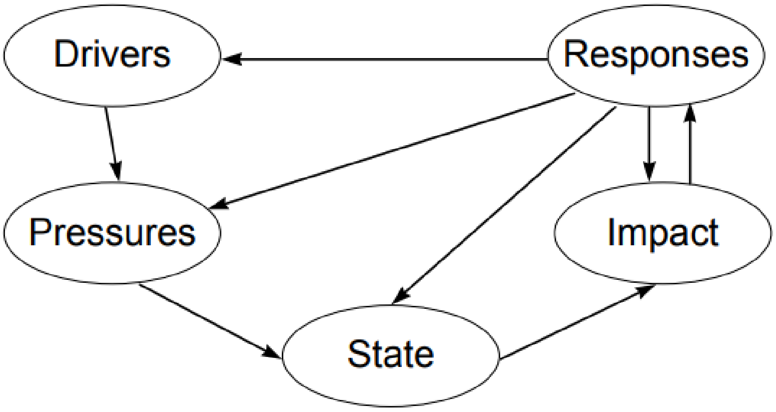

Figure 1 The DPSIR model. Arrows indicate the relationship between the components and illustrate the cyclical approach (Smeets and Weterings 1999, 6)

Managing complex phenomena like climate change requires taking a structured approach to describe cause and effect produced by dynamics between different components in environmental systems. The DPSIR model, proposed by the CIS within the WFD, allows analysing how anthropogenic activities trigger changes in the aquatic environment (EC 2003). Despite its simple structure it is regarded to be a viable tool for comprehensively describing “complex cause-effect relationships between human activities, the environment, and society” (Patrício et al. 2016, 6). Subsequently, chapter 3 contains a more detailed outline of the components and the functioning of the DPSIR model.

2.1.2. Materials

Literature about the development of the DPSIR model and its modification for different purposes informs about the terminology and the functioning of the framework. Non-legally binding guidance documents of the CIS and European water policy highlight the need to integrate climate change into River Basin Management Plans (RBMPs). By analysing different approaches towards managing climate change induced alterations of the environment in water management, a literature review shows how climate change has previously been integrated within individual components of the model.

2.2. Case Study: Testing the Model and Evaluating its Functioning by the Example of the Durance River Catchment

The case study aims to show that the model developed in the theoretical part is a viable tool to "place [...] side-by-side environmental and socio-economic interests" (Mateus and Campuzano 2008, 29). Its application follows the stepwise approach of the precursor model, the DPSIR framework as described in chapter 3.

2.2.1. Methodological approach

The answer to question 2 is developed by analysing how climate change and existing anthropogenic pressures potentially impact components of the water body state in the Durance River. The results provide input to addressing question 3 and 4.

Question 3 consists of analysing how potential changes in the water budget of the Durance River could produce constraints for hydropower production.

The answer to question 4 assesses how changes in the state elements could affect the water quality status. Overall, the case study is structured along the DPSIR-CC model, which the theoretical part describes in detail. To assess in a qualitative to semi-quantitative way how direct impacts of climate change on drivers and on the state of the water body could produce additive effects, the linkage between the components is analysed by using tables. The case study is structured into the following steps: Identification of anthropogenic drivers and their specific use of surface water in the Durance catchment.

1. Identification of anthropogenic water uses relevant to the case study (drivers)
2. Assessment of direct impacts of climate change mitigation policies and climate change adaptation on those drivers of water uses (climate change-drivers)

3. Identification of pressures directly resulting from drivers (drivers-pressures)
4. Analysis of the additive effects produced by direct impacts of climate change on the drivers and direct consequences on the components of the water body state (drivers-pressures-state-climate change)
5. Discussion of potential consequences of these changes in state for hydropower production
6. Evaluation of potential impacts on the ecological and chemical status of surface water bodies by including the results from the previous steps (drivers-pressures-state-impact)

2.2.1.1. Identification of Anthropogenic Drivers

First, anthropogenic activities in the catchment and water use practices for each driver are identified. This is important, because changing climate conditions could produce entirely different implications, even within one driver. For example, energy production could either be understood as energy generation from hydropower or from thermal power plants. While thermal power plants require water at a certain amount and temperature level, hydropower production directly relies on the amount and the timing of river runoff. If water temperature increases, the efficiency of the thermal power plant decreases; however, river runoff hydropower plants or water storage reservoirs would not face significant consequences at elevated water temperatures. This complexity related to the assessment of the relation between drivers and climate change explains why, prior to the analysis for each of the anthropogenic activities, a clear description of specific water use should be subject to the case study. In the following example, the driver “agriculture” is defined as “agricultural irrigation”, the driver “energy production” as “hydropower generation”, the driver “domestic water demand” is analysed with regards to the pressure “water abstraction”, the driver “tourism and leisure” contains water use for “irrigation”, and the driver “industry” is defined as “water use for cooling purposes”.

2.2.1.2. Climate Change Mitigation and Climate Change Adaptation Versus Drivers

This chapter evaluates if and how climate change mitigation policies and climate change adaptation could directly trigger changes in anthropogenic activities.

The following table hence illustrates if the human activity is either subject to climate change mitigation policies or if global warming directly influences the anthropogenic water use and triggers adaptation actions of the driver.

Climate change mitigation is defined as actions undertaken either to curb or to avoid Greenhouse Gas (GHG) emissions, or measures which reduce the presence of GHG in the atmosphere (IPCC 2018). Mitigation influences anthropogenic activities, if, for example, a driver contains a large GHG-emission saving potential, e.g. hydropower production; or if the sector is subject to policy measures which aim to reduce greenhouse gas emissions from large emitters, e.g. the industrial sector.

Climate change adaptation is “the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities” (ibid). Adjustment to climate change in human water use depends on the climate signals which force the driver to change water use practices.

Table 2. 1 The influence of climate change mitigation policies and climate change adaptation on drivers of water use

Climate change		**Mitigation**	**Adaptation**	**Total**
Drivers	Agriculture (irrigation)	+	+	2+
	Energy production (hydropower)	+	+	2+
	Domestic water demand			
	Tourism/leisure (irrigation)		+	+
	Industry (cooling)	+	+	2+

Table 2.1 illustrates, if climate change mitigation policies and climate change adaptation influence drivers of anthropogenic water use. The sign “+” indicates that climate change adaptation or climate change mitigation influences water use practices of the driver. Adding up the results for each driver allows assessing the climate-sensitivity of the individual water use practices in a qualitative to semi-quantitative way. The results from table 2.1, illustrated in the right column, give the total amount for each driver and serve as an input for the next step in the case study.

Agricultural irrigation reacts to climate change mitigation policies if irrigated agricultural land is used to cultivate biomass with the aim to replace fossil fuels as energy source, +. Climate change adaptation influences irrigated agriculture, since global warming and decreasing precipitation affect plant growth. Projections on the magnitude of the impact are complex due to multiple factors determining agricultural irrigation practices, such as crop water demand, technology, socio-economic development etc., +.

Hydropower production is promoted by climate change mitigation policies, +, since it contains a high potential of reducing GHG emissions (Berga 2016, 315). The generation of energy from hydropower depends on the river flow in volume and timing.

If, at warmer atmospheric temperatures and lower levels of precipitation, water resources get scarce, hydropower production could get less efficient. Climate change adaptation of hydropower plants, however, strongly depends on the location of the installation. For runoff plants fed from alpine glaciers in central Europe, it is projected that warmer temperatures could increase the amount of river runoff in the near future, while rivers, which predominantly depend on melt water from snow in southern European mountains could experience more low flow regimes (EEA 2016a).

Independent of the impact on hydropower, however, both types at different locations adapt to changes in the amount and timing of river runoff, +.

Domestic water demand is not expected to be strongly influenced neither by climate change mitigation nor by climate change adaptation, because other factors such as demographic development, urbanisation, and technology are predominantly determining the amount of water used for domestic purposes.

Irrigation of leisure facilities is influenced by climate change mitigation policies in a similar way as agricultural irrigation practices react to changes in temperature and precipitation, +. Tourism and leisure do neither contain a strong emission reduction potential, nor do they produce large amounts of GHG. Therefore, those sectors are not considered as sensitive to climate change mitigation.

Accounting for 19% of sectoral greenhouse gas emissions in 2014, **industrial sectors** are, overall, implementing climate change mitigation practices, + (EEA 2016b).

Industrial water use for cooling purposes adapts to changing climate conditions if, at warmer water temperatures, more water needs to be abstracted to compensate losses in the efficiency of the cooling process. Therefore, climate change adaptation might trigger a higher water demand, +.

The right column assesses qualitatively to semi-quantitatively the influences of climate change mitigation policies and adaptation on each of the anthropogenic activities.

Agricultural irrigation, energy production from hydropower and industrial water use for cooling are the most climate-sensitive drivers, 2+; while irrigation for tourism and

leisure reacts with adaptation measures +, domestic water demand is considered to experience stronger influences from other factors than changing climate conditions.
The results of this assessment serve as an input to the next step, which consists of analysing the link between drivers and anthropogenic pressures exerted on the water body.

2.2.1.3. Anthropogenic Drivers and Directly Resulting Pressures

The evaluation of pressures is limited to an assessment of the consequences directly produced by each of the anthropogenic drivers according to their specified water use. Notwithstanding the fact that diffuse pollution from agriculture results from agricultural activities, the following analysis disregards substance pollution from agriculture, since agricultural irrigation, defined as water use practice in this example, solely results into water abstraction. The same applies to industrial water use. Point source pollution is not part of the analysis, since water use for cooling purposes is only assessed with regards to quantitative water use.

Table 2. 2 The relationship between anthropogenic drivers and the directly resulting pressures

Drivers **Pressures**	Agriculture (irrigation)	Energy production (hydropower)	Domestic water demand	Industry (cooling water)	Tourism/leisure (irrigation)	**Total**
Water abstraction	3+	3+	+	3+	2+	12+
Morphological changes		3+				3+
Hydrological changes		3+				3+
Thermal pollution				3+		3+

Table 2.2 describes the anthropogenic pressures and attributes them to each of the drivers. To account for influences of climate change on anthropogenic drivers, the result for each driver from table 2.1 is included in table 2.2.
The results from agricultural irrigation, 2+, in table 2.1 added to the pressures water abstraction yields 3+. The same applies to hydropower production, 3+, and industrial water use for cooling, 3+. Domestic water demand, which reacts neither to climate mitigation policies nor by applying adaptation actions, hence accounts for + in water abstraction. Considering that tourism/leisure potentially adapts water use practices for irrigation with global warming, the pressure “water abstraction” is considered to amount to 2+. The right column sums up the total amount for each of the pressures in order to

semi-quantitatively assess in the next step the influences of each pressure on the state of the water body. Adding up the results from the drivers yields for water abstraction the total value of 12+. Morphological changes, hydrological changes and thermal pollution are exerted by one driver respectively, hence they account in total each for 3+.

Water abstraction and hydrological changes, both modify the river runoff by reducing the amount of volume flow (temporarily or permanently) or change its dynamics as a result of physical barriers. Hence, irrigation, industrial cooling purposes, and hydropower production could be categorised within the pressures causing hydrological changes. Table 2.2, however, accounts for water abstraction separately, because of three reasons. First, a decrease in the amount of available water could severely affect water quality by reducing the dilution capacity of substances, see subsequently in table 2.3 Second, at the prospect of increasing near surface temperatures and decreasing precipitation the amount of available freshwater could create severe constraints for anthropogenic activities as well as for the environment. Third, discerning the impacts of a reduction in water quantity and alterations in the hydrology of streams is relevant, if the water abstracted is supplied and subsequently discharged outside the catchment.

Water abstraction: Agriculture abstracts water for irrigation purposes, 3+. The amount of water required depends on multiple factors, such as vegetation, e.g. crop type and cultivation method, climate conditions, or irrigation technology. Hydropower installations abstract water temporarily either by spinning turbines with flowing water or by releasing water stored in reservoirs at periods of peak energy demand (International Hydropower Association n.d.). Despite discharging the water to the natural environment, both types of hydropower installations abstract water, thereby strongly altering the natural river flow in amount and dynamics, 3+. Freshwater is withdrawn to supply domestic water demand**.** This includes water use for hygiene and sanitary purposes, for household uses and cooking purposes as well as drinking water demand, +. Industries abstract water for cooling purposes, 3+, and discharge it at higher temperatures, thereby causing thermal pollution, 3+. Water abstraction for tourism and leisure is used similarly to agricultural irrigation, 2+.

The construction and operation of hydropower installations change the hydrology and morphology of water environments 3+. Dams, weirs, and reservoirs as well as artificial canals alter the natural quantity and dynamics of river flow, and, inter alia, impact sediment transport in rivers.

2.2.1.4. Direct Effects of Climate Change and Pressures on the State of Surface Water Bodies

Based on the results from table 2.2, this step assesses how climate change directly influences the state of water bodies. By including the total amount of each pressure, this illustrates how climate change and anthropogenic pressures, themselves influenced by climate change, could produce additive effects.

Table 2. 3 Direct effects of climate change and existing pressures on state elements of surface water bodies

State		**Direct impact: Climate change**	**Pressures**				**Total**
			WA[2]	**MC[3]**	**HC[4]**	**TP[5]**	
Hydrology	Water level and discharge	+	12+		3+		16+
	Minimum flow	+	12+		3+		16+
River continuity					3+		3+
Morphology	Bank dynamic			3+			3+
	Riverbed structure			3+			3+
	Riverbank vegetation	+		3+			4+
Physicochemical elements	Temperature	+			3+	3+	7+
	Oxygen balance	+					+
	Salt content	(+)					(+)
	Acidification	(+)					(+)
	Nutrient content	+					+
Chemical status	Substance concentration	+	12+			3+	16+

Table 2.3 illustrates the water body state elements, which directly react to climate change induced alterations of the environment as well as to anthropogenic pressures (see table 2.2).

Hydrology: Water level, discharge, and minimum flow are directly influenced by global warming, because the river flow regime depends on atmospheric temperature conditions and rainfall patterns. Additionally, the amount and timing of river runoff fed from snow or ice is strongly influenced by near surface temperature. At the presence of global warming, the storage capacity of mountains decreases, thus less water is supplied to rivers. Low flow regimes, particularly during hot summer months could occur more frequently and at longer duration if increasing atmospheric temperatures impact the

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[2] Water abstraction
[3] Morphological changes
[4] Hydrological changes
[5] Thermal pollution

quantity of freshwaters, +. Water abstraction, 12+, and hydrological changes, 3+, alter minimum flow as well as water level and discharge. In total, hydrological state elements are subject to strong influences from anthropogenic pressures as well as from climate change, 16+.

Morphology: Riverbank vegetation responds to atmospheric warming, since plants are sensitive to changes in soil moisture as well as the direct supply of water as rainfall and temperature levels. Consequently, global warming directly influences riverbank vegetation +. Morphological changes are caused by the construction and operation of hydropower installations impacting sediment transport, riverbed structure, and bank dynamic 3+. Hence, bank dynamic and riverbed structure are less impacted by pressures and climate change, 3+, than riverbed vegetation, 4+.

Physicochemical elements: Water temperature reacts to changes in atmospheric temperature conditions, +. Additionally, thermal pollution causes water temperature to rise, 3+. Fluctuations in river flow, which result from physical barriers, impact water temperature, 3+.

Table 2.3 describes only changes directly resulting from the specific water use. However, global warming and anthropogenic pressures are influencing **oxygen balance** through several factors directly and indirectly with various processes involved, +. A brief outline of the most significant consequences stresses the importance of oxygen interacting with several other water quality parameters. First, water temperature and the solubility of oxygen are inversely correlated; if, with climate change, water temperature increases, the solubility of oxygen decreases. Low flow regimes in summer coupled with a strong rise in temperatures could speed up oxygen depletion in surface waters. Second, at higher levels of salinity, the amount of oxygen dissolved in water decreases. Third, anoxic conditions in water bodies, indicated by the absence of dissolved oxygen, could result from eutrophication. A higher availability of growth enhancing factors, such as sunlight, Carbon Dioxide (CO_2), and nutrients, promotes the excessive production of algae, consequently leading to eutrophication of waters. (For a description of the correlation between nutrient content, acidification, and climate change, see the following paragraph.) Strongly increasing presence of algae could impact the transparency of water, hence causing plants to die off. Surging oxygen consumption as a result of decomposing biomass could lead to anoxic conditions in water bodies.

While changes in atmospheric temperature and rainfall patterns play a rather minor role in influencing **acidification levels** in water, it has been found that atmospheric CO_2 concentrations could directly influence pH in surface waters (Weiss et al. 2018).

From data collected in freshwater reservoirs in Germany, Weiss et al. detected that pH levels fell approximately 0.3 from 1981 to 2015 (ibid, 327). Despite indicating a strong effect in the surface water conditions, due to the complex interactions of land and sediment as well as highly heterogeneous properties of surface waters a general conclusion for all surface waters cannot be drawn (ibid, 330). Despite a direct correlation between atmospheric temperature conditions, low flow regimes, deoxygenation, and acidification exists, the latter being strongly influenced by other parameters and hence not analysed in detail, +.

Climate change induced alterations of the environment could affect the **nutrient content** in surface water bodies, +. From observations in the River Tame, England, it was found that there is an “inverse relationship between phosphorous levels and flow” (Whitehead et al. 2009, 103), which exacerbate during summer months, thereby causing strong alterations of phosphorous levels. While flushing from flood events could increase the nitrogen load, particularly after dry summer months, heavy rains enhance the leaching of nitrogen from agricultural soil (ibid, 106). Additionally, higher water temperatures and lower concentrations of oxygen in surface water could enhance the mobilisation of phosphorous present in riverbeds (Arnell et al. 2015, 107).

According to this analysis, water temperature is the most sensitive physicochemical element, 7+, while oxygen balance, nutrient content, acidification, and salt content are considered to react less strongly to pressures and climate change, +. Due to the complex interplay of multiple factors involved in determining the physicochemical condition of waters, those results cannot reflect all aspects involved, yet aim to give a broad overview of potential effects.

The chemical status of surface water bodies indicates the concentration of substances as defined by the Environmental Quality Standards (EQS) foreseen in the Environmental Quality Standards Directive (EQSD; 2008/105/EC).

At the prospect of decreasing precipitation and warmer atmospheric temperatures, the amount of water present in surface water bodies gets reduced.

This affects substance concentration, since the dilution capacity of rivers decreases, +. Additionally, higher temperatures enhance chemical reactions, which potentially favour the production of harmful substances. Studies about climate change impacts on drinking water quality of the Rhine and the Meuse River observed that low river flow significantly impacts water quality (Sjerps et al. 2017, 1693). For both rivers it was detected, that projected prolongation in low flow regimes could cause the concentration of the studied substances to “increase up to ta factor 3-4” in the Meuse River (ibid). Furthermore, anthropogenic water abstraction impacts the amount of river flow, which could enhance an increase in the concentration of organic and chemical pollutants, 12+. Thermal pollution resulting from industrial water use for cooling purposes affects water quality, because water discharged at higher temperatures could lead to similar effects as those discussed for atmospheric warming, 3+. Overall, the results show that water bodies are subject to strong anthropogenic pressures and direct effects of climate change, 16+.

2.2.1.5. Potential Consequences for Hydropower Production

This chapter addresses question 3 by analysing the results obtained from the answer to question 2. First, according to the functioning of the hydropower installations in the Durance catchment, it is determined which component of water body state influences the operation of hydroelectric power plants. Then, with the information in table 2.3, it is analysed how, with climate change and existing anthropogenic pressures, a change in the state components relevant for the generation of hydroelectricity could produce constraints to the operation of hydropower installations.

2.2.1.6. Potential Impacts on the Ecological and the Chemical Status of Surface Water Bodies

This chapter addresses the fact that existing anthropogenic pressures and potential impacts of climate change could pose a threat to achieving the goals of the WFD. By the example of the Durance River, this section of the thesis aims to highlight the importance of integrating long-term projections on and potential implications of climate change into RBM.

Therefore, the answer to question 4 analyses how changes in natural conditions of the water body could create consequences for the achievement of the WFD’s goals. The results obtained from tables 2.1 to 2.3 serve to identify the most vulnerable state elements. Data on the current ecological and chemical status of the Durance River support the impact assessment.

The answer to question 4 is structured into the following steps:

First, the identification of the current quality status of the water body.

Second, the identification of the most vulnerable state element based on the results from the previous chapter.

Third, the impact assessment, which analyses how biological quality elements could be affected by changes of the weakest state element and direct impacts of climate change.

The evaluation of the results includes a brief discussion of potential consequences for the achievement of the WFD's goals.

2.2.1.6.1. Identification of the Current Ecological and Chemical Status

For each state element, biological, physicochemical, hydrological, morphological, and chemical the published data of river basin authorities are included in table 2.4.

The water quality status of surface water bodies is determined by natural conditions and anthropogenic pressures. Natural conditions are measured with parameters obtained from ecological quality status elements and chemical quality conditions.

The ecological quality status of surface water bodies is determined by using the following quality status elements (EEA 2018b).

- Biological quality elements (BQE) according to the composition and abundance of phytoplankton, macrophytes, phytobenthos, benthic invertebrate fauna and fish. Physicochemical and hydro-morphological elements support the classification of BQE
- Physicochemical elements are assessed along general parameters, such as water transparency, thermal regime, oxygen conditions, salinity, acidification status, nutrient conditions, nitrogen conditions, phosphorous conditions, and river basin specific pollutants.
- Hydrological and morphological quality elements indicate the tidal regime, river continuity, sediment transport, and the hydrological regime of surface waters.

The assessment of the chemical status of surface water bodies is foreseen in European-wide binding provisions for certain substances and national-level regulations on controlling river basin specific pollutants, which are considered as part of the ecological status assessment. Article 16 WFD foresees the establishment of a list of priority substances which pose a significant risk to the environment. The first list, established in

2001, subsequently was replaced by Annex II of the Environmental Quality Standards Directive (EQSD; Directive 2008/105/EC). EU-wide binding Environmental Quality Standards (EQS) are defined for priority or priority hazardous substances in surface water bodies. According to Article 4 and Annex V 1.4.3 WFD, to reach overall good water status, Member status must comply with the quality standards listed in the EQSD.

2.2.1.6.2. Identification of the Most Vulnerable State Element

Table 2.4 places side by side the water body state elements, the pressures by including the information from table 2.3, indicates from which state elements potential impacts could arise for BQE (by the example of phytoplankton). The right column in table 2.4 displays the current status as obtained for each state element used in the water quality assessment. This aims to evaluate which elements of water body state are most affected by existing pressures and by the direct impacts of climate change.

Table 2. 4 The state components of the surface water body, the pressures including direct effects of climate change, impacts on biological quality indicators resulting from changes in the state, and the current status of the water body

State		Results from table 2.3 (Pressures and climate change)	Impact on BQE (phytoplankton)	Current Status
Hydrology	Water level and discharge	16+	✓	High/Good/Moderate/ Poor
	Minimum flow	16+		
River continuity		3+		
Morphology	Bank dynamic	3+		High/Good/Moderate/ Poor
	Riverbed structure	3+		
	Riverbank vegetation	4+		
Physico-chemical parameters	Temperature	7+	✓	High/Good/Moderate/ Poor
	Oxygen balance	+	(✓)	High/Good/Moderate/ Poor
	Salt content	(+)	(✓)	High/Good/Moderate/ Poor
	Acidification	(+)	(✓)	High/Good/Moderate/ Poor
	Nutrient content (nitrogen, phosphorous)	+	✓	High/Good/Moderate/ Poor
Chemical status	Substance concentration	16+	✓	High/Good/Moderate/ Poor
			Elevated concentration of priority substances according to EQSD	

To account for the pressures and direct effects of climate change exerted on each of the state elements, the results from table 2.3 are included in table 2.4.

The sign "✓" shows if the BQE is directly reacting to a change in the state element, indirect effects resulting from the interplay of multiple factors are indicated with "(✓)".

Hydrology: Water level and discharge as well as minimum flow, both are affected by climate change, water abstraction, and hydrological changes, 16+.

River continuity is altered by hydrological changes resulting from the operation of hydropower installations, 3+.

Morphology: Bank dynamic and riverbed structure are both subject to morphological changes, 3+. Riverbank vegetation is directly affected by climate change and by morphological alterations, 4+.

Physicochemical elements: Temperature levels change if water used for industrial cooling processes is discharged at higher temperatures, 3+, and intermittent flow regimes affect water temperature levels, 3+. Furthermore, water bodies react to changes in atmospheric temperatures, +. Summing up those effects yield a total of 7+.

Because oxygen balance, acidification, and salt content are influenced by the interaction of multiple factors, those state elements will not be part of an in-depth analysis.

Substance concentration, determining the **chemical status** of surface water bodies, is affected by direct impacts from climate change as well as by water abstraction and temperature pollution, 16+.

2.2.1.6.2. Impact Assessment

First, table 2.4 developed in the previous step allows evaluating the effect of the pressure for each state element and, compared with the information about the current status, this shows which of the state elements is most vulnerable.

Second, it is analysed how changes in the state elements most vulnerable could impact the BQE, thereby potentially deteriorating the ecological quality status. Assessing the chemical quality status, as foreseen in the EQSD, is not subject to detailed analysis in this thesis.

Depending on the BQE used for the assessment of ecological quality status, the impact results in changes in composition, abundance, age structure of biological indicators, or influences the production of biomass.

The composition and abundance of algae, phytobenthos and macrophytes react to changes in nutrient content, while composition and abundance of benthic invertebrates are highly sensitive to organic pollution. At the presence of organic pollution and pressures on physicochemical or chemical conditions, algae and phytobenthos might change. Macrophytes and benthic invertebrates react both to changes in hydro-morphology and other chemical or physicochemical parameters. Benthic invertebrates are additionally sensitive to nutrient content. While hydro-morphological changes are not severely impacting the composition and abundance of algae and phytobenthos, fish population could be strongly affected. Additionally, alterations in composition, abundance, and age structure of fish could result from pressures causing organic pollution, nutrient load, or alterations in other chemical or physicochemical conditions. Despite not explicitly included in table 2.4, organic pollution causes effects on algae, phytobenthos, fish, and benthic invertebrates, while macrophytes show a lower sensitivity to organic pollution.

To determine if changes in the state elements could affect biological indicators, table 2.4 attributes the sign “✓”, impacts which involve the interaction of multiple factors are indicated with “(✓)”. The following description gives an overview of those impacts which could trigger alterations in composition and abundance of phytoplankton, one of the most frequently used BQE.

Hydro-morphological changes affect the composition and abundance of phytoplankton rather indirectly through water level fluctuations. Accordingly, a study conducted by Schönbrunner et al. “[r]epeated drying and wetting resulted in elevated phosphorous release” (2012, abstract). Hence, intermittent high and low flow regimes resulting from anthropogenic pressures and climate change could promote the mobilisation of phosphor, a crucial element for phytoplankton production.

If **physicochemical conditions** change, phytoplankton could alter in composition or abundance of species. Phytoplankton bloom is strongly correlated with light conditions and the presence of nutrients, particularly that of phosphor.

Temperature, which determines the lifecycle and productivity of biologic organisms, affects “community structure and distribution” (Schabhüttl et al. 2012), although in a “highly context-specific” (Striebel et al. 2016, abstract) manner.

The interaction of several factors, such as changes in salt content, coupled with altering light conditions, and ph levels, could influence the composition of phytoplankton (e.g. Chakraborty et al. 2011; Lionard et al. 2005)

Oxygen balance in waters affects phytoplankton, since anoxic conditions, a typical consequence of elevated water temperatures and euthrophication, “have a considerable effect on both organism distribution and biogeochemical cycling.” (Arnell et al. 2015, 106).

Acidification affects the composition of phytoplankton communities indirectly at the presence of other factors.

The **chemical status** of surface water bodies influences the composition and abundance phytoplankton, if the concentration of organic and chemical substances present in water bodies increases.

From table 2.4 the following could be concluded: First, the total amount of “+” shows the elements most affected by pressures and the impacts of climate change. Hydrological quality elements and substance concentration, both indicated with 16+ are most prone to change with climate change induced alterations of the environment and existing anthropogenic pressures. Second, with the information on the current status classification it is assessed how changes in the weakest elements could cause BQE to deteriorate.

Notwithstanding the fact that the failing to reach good chemical status could likewise hinder the achievement of the WFD’s goals, potential effects on the concentration of substances in surface water body is part of the impact assessment, yet not subject to a detailed analysis.

The results obtained with the impact assessment serve as input for response measures, which aim to conserve or restore natural conditions. If, for example, hydrological state elements are at high status and the chemical water body status is classified as good, conservation measures should be targeted towards maintaining good chemical status. If one of the state elements is at moderate status, restoration measures need to provide for potential impacts on the state element reacting to existing anthropogenic pressures and potential global warming.

The application of the DPSIR-CC model hence aims to provide input for developing robust response measures in water management by integrating projected changes in climate conditions and their potential impacts on the water environment. Therefore, the development of response measures tackling potential impacts on water quality status is outside of the scope of this thesis.

2.2.2. Materials

The case study includes published data from RBM authorities in the Rhône River Basin. In addition to that, it is guided by the results of the project R^2D^2 2050 “Risk, water Resources and sustainable Development within the Durance river basin in 2050” (Sauquet et al. 2015) which assesses future water needs of anthropogenic activities in the light of changing climate conditions. This is complemented by global and regional climate projections, particularly data from Magand (2014), the Intergovernmental Panel on Climate Change (IPCC) and hydrologic models, projecting potential changes of the flow regime in the Durance catchment. Additionally, literature on hydropower in the light of changing climate conditions provides input to the case study. Studies about climate change impacts on the ecological and chemical quality of surface water bodies give an overview of the current research and inform the impact assessment.

Data and reports published by the Rhône RBM authorities, official reports on the status of water bodies drafted by the EEA complement the sources.

3. Theoretical Part: Development of the DPSIR-CC Model

This chapter explains the structure and the functioning of the existing DPSIR model in water management. A review of current literature about previous modifications of the DPSIR model provides the basis of integrating climate change into the framework.

3.1. The Driver-Pressure-State-Impact-Response Model

The DPSIR model is an indicator-based analytical framework which helps to assess the relationship between the components in order to track changes in environmental systems.

3.1.1. The Driver-Pressure-State-Impact-Response Model in Water Management

Initially created as Stress-Response model by Rapport and Friend (1979), the DPSIR-model was extended by the OECD in 1991. The EEA has applied the framework since 1995 as basis for environmental reporting.

The DPSIR model is used to describe complex phenomena of real-world processes; however, it allows evaluating rather a qualitative level than a quantitative level of impacts. To apply the framework in different contexts of policy making, it has been subject to several modifications. Smith et al. (2014) apply the model to the marine environment to describe several interlinked cycles of drivers, states, impacts, and responses triggered by one pressure. To describe socio-economic processes, Cooper (2013) extended the model to Driver-Pressure-State-Welfare-Response (DPSWR); adapted to the policy context of the World Health Organization (WHO), the Driver-Pressure-State-Exposure-health Effects-Actions (DPSEEA) links environmental aspects to impacts on health (von Schirnding, 2002).

Since the adoption of the WFD, RBM follows a structured approach on monitoring and evaluating the achievement of environmental objectives. To support Member States with the implementation of the WFD, working groups within the CIS developed non-legally binding guidelines. Guidance Document n°3, drafted by Working Group 2.1, describes how the DPSIR model could serve as a basis for the “Analysis of Pressures and Impacts” (EC 2003a).

3.1.2. Environmental Indicators in the Driver-Pressure-State-Impact-Response Model

Flexible and adaptable to different environmental issues, the model allows defining indicators for each of the components dependent on the system of interest. To support policy making with information on environmental conditions and potential implications human activities could produce for ecosystems, the DPSIR model provides a structure to apply indicators for drivers, pressures, state, impacts, and response respectively. Depending on the environmental system subject to the analysis, indicators function as an “observed value representative of a phenomenon of study” (Gabrielsen and Bosch 2003, 5). According to Smeets and Weterings (1999, 5), indicators

1. Inform policy making about environmental problems and provide a basis to evaluate their implications
2. Deliver an overview of the most pressing issues to support policy development by describing the cause-effect relationship between the system's components
3. Identify the impacts of response measures

In the following case study, "descriptive indicators" for each of the components, driver, pressure, state, impact, and response, aim to highlight the first two purposes as stated in Smeets and Weterings (1999, 5). Based on projected changes in climate conditions and their implications on anthropogenic activities as well as potential impacts on the environment, the case study intends to discuss the question "What is happening to the environment and to humans?" (ibid, 8).

Despite the simple structure of the system, the DPSIR hence provides a conceptual framework to describe complex interactions of components within the "causal chain that links human activities to their ultimate environmental impacts" (ibid, 7).

3.1.3. The Pressure-Impact Assessment in Water Quality Monitoring

Prior to the implementation of the first RBMPs in 2009, Member States defined River Basin Districts (RBD) within their territory and identified competent authorities in water management. The pressure-impact assessment undertaken at sub-catchment level, is based on the characteristics of each water body. First, each surface water body is categorised either as river, lake, transitional water, coastal water, artificial water, or as heavily modified water body. Within those categories, surface water bodies are assigned to types. Subsequently, type-specific reference conditions are defined for each water body type (Annex II WFD). Then, depending on the results of the pressure-impact analysis, water body types are sub-divided into smaller entities.

The identification of pressures assesses "type and magnitude of the significant anthropogenic pressures" (ibid, 1.4). Significant anthropogenic pressures are defined as "*any pressure that on its own, or in combination with other pressures, may lead to a failure to achieve the specified objective*" (EC 2003a, 14). The pressure-impact analysis thereby assesses how significant Pressures could pose a risk to achieving the environmental objectives. Annex V WFD describes the quality parameters, which determine the ecological status and ecological potential of water bodies. They contain biological elements chemical and physicochemical elements, specific pollutants, and hydro-morphological elements supporting the biological elements. The classification is governed by the so called “one out all out principle”, which implies that the weakest component determines the status of the water body.

BQE are subdivided into flora, benthic invertebrates, and fish. If the amount and composition of biological elements is “undisturbed”, the status is classified as high, “nearly undisturbed” indicates good status, “slight disturbance” moderate status, and “major alterations” means poor status, and severe alterations represents a bad status (ibid, 19).

Chemical and physicochemical elements contain general and specific pollutants; the WFD foresees European-wide limitations for specific pollutants, while for general pollutants there are no legally binding numerical limitation.

Hydro-morphological elements are complementing other quality components and could play a crucial role if water bodies are at risk of failing to achieve ecological and chemical good status.

Throughout the risk assessment process, uncertainties could originate from dynamics produced when different quality elements interact, temporal shifts in the measurability of certain pressures, as well as with data collection gaps.

Each status classification of individual water bodies contains a scale indicating the confidence level at which the status was established.

Based on the first pressure and impact assessment, operational monitoring networks and the initial characterisation of water bodies had to be set up until 2006 (Art.8 WFD). Information from monitoring and existing data feeds into the economic analysis which contributes to the development of the Programme of Measures (PoM) (ibid, Art.11). Considering the current status, the pressures-impact assessment evaluates how potential changes in existing pressures could influence the likelihood of failing to achieve good ecological status by the end of the RBM cycle. The second RBMPs (2016-2021) are based on the outcome of the pressure-impact assessment in the first implementation cycle (2009-2015), the current status of water bodies, and the specific objectives. Surface water bodies at risk of failing their specified objective within the RBD are subject to additional monitoring and specific measures (EC 2003a, 9).

3.1.4. The Components: Driver-Pressure-State-Impact-Response

The DPSIR-model proposed by the Guidance Document n°3 (EC 2003a, 13) contains the following components for which indicators are identified on a case-by-case basis:

Drivers	are anthropogenic activities which potentially impact the environment; e.g. agriculture, industry, urbanisation, energy production,
Pressures	result from the direct effect of the drivers; e.g. water abstraction for agricultural irrigation, hydro-morphological alterations caused by hydropower production, point pollution from industrial water discharges,
State	describes the condition of the water body resulting from both natural and anthropogenic factors, such as climate, geology, and human demand for water,
Impact	represents the environmental effect of the pressure, e.g. the degradation from “good” to “moderate” class e.g. as a result of changes in composition or abundance of biological quality elements,
Response	implies the measures taken to improve the State of the water body; e.g. the RBMP or the PoM foresee the restoration of artificially changed riverbeds to improve the hydro-morphological conditions.

The analysis of the interrelationship between the components and implications of change in the state follows a stepwise approach. According to the Guidance Document n°3 it is structured in the following phases (ibid, 23):

3.1.4.1. Identification driving forces and pressures
3.1.4.2. Identification the significant pressures
3.1.4.3. Assessment of impacts by comparing the state to the specific objectives
3.1.4.4. Evaluation of the likelihood of failing to meet the objectives

Each stage is undertaken in relation to the characterisation of the water body (Art.5 WFD), the objectives set from the previous pressure-impact analysis, and the overall objectives in Article 4 WFD.

3.1.4.1. Identification of Driving Forces and Pressures

Driving forces are considered as anthropogenic activities, determined by socio-economic dynamics and climate conditions. Projections of long-term trends are complex as changes depend on multiple aspects and external factors. Furthermore, several drivers, for example agriculture and tourism could trigger the same pressure hence potentially creating conflicts in water demand.

Pressures are the direct result of either one or multiple drivers. Anthropogenic pressures are triggered by anthropogenic activities altering the river flow regime or water quality. Additionally, they could originate from point or diffuse sources impacting water quality.

3.1.4.2. Identification of Significant Pressures

After identifying all potential pressures, those potentially causing failure to achieve the WFD’s objective are determined. Knowledge about the characteristics of a catchment and a thorough understanding of the objectives are required to identify significant pressures. Spatial aspects such as impacts on tributaries and waters up- or downstream the assessment are included in this process (EC 2003a, 28). Temporal aspects could become relevant if there is a time lag between the pressure and its effect on the water body.

3.1.4.3. Impact Assessment

The state of surface water bodies is determined by biological, physicochemical, and supporting hydro-morphological elements (ibid, 34).

The impact depends on the deviation of the current state from the specific objectives for each water body, which both are determined by the water body classification and the reference condition. Consequently, the pressure-impact assessment analyses how significant pressures could trigger a change in the system by altering one of the environmental quality elements, thereby producing a deviation from the reference condition. Additionally, it is important to consider that multiple pressures could produce an unexpected exacerbation of state, while some pressures do not directly cause the state to change but still reducing the “probability of occurrence of favourable circumstances” (ibid). Particularly when it comes to hydro-morphological elements, Impacts are not easily quantifiable. In that case the risk assessment is limited to analysing how effects on the biological or chemical elements could trigger changes in the quantity or dynamics of river flow, in the residence time of water, or in hydro-morphological elements.

The deterioration of water quality class results from alterations of the parameters determined for the biological, hydro-morphological, physicochemical, and chemical quality status. BQE are subject to changes mainly in composition, abundance, phenology, or age structure. Chlorophyll concentration is the parameter to measure eutrophication. Hydro-morphological quality elements influence changes in the quantity or dynamics of stream flow, in the residence time of water, or concerning depth and width variation as well as morphological characteristics referring to the structure and of the riverbed and riparian zones.

Physicochemical quality elements are: Transparency, oxygen content, the presence of nutrients, salinity, acidification status, or turbidity. Additionally, national-level regulations on controlling river basin specific pollutants are considered as part of the ecological status assessment. The chemical status of surface water bodies is determined by EU-wide binding rules for priority substances according to the EQSD.

3.1.4.4. Evaluation of the Likelihood of Failing to Meet the Objectives

Annex V WFD foresees that "an assessment of the likelihood that surface waters bodies […] will fail to meet the environmental quality objectives" is based on the objectives set for each water body. This consists of comparing the state of the water body, established according to Annex II WFD, with the threshold values for quality standards in Annex V WFD. Since monitoring is based on a "conceptual model" (EC 2003a, 43), a dynamic approach allows to improve "with time as new data are obtained and as the model is tested" (ibid).

3.2. The Development of the Driver-Pressure-State-Impact-Response-Climate Change Model

This chapter aims to create a model which allows evaluating the direct and indirect impacts of climate change on driver, pressure, state, impact, and response. Literature on climate change in river basin management and its implications on the individual components of the system provide input for the development of the "Driver Pressure State Impact Response-Climate Change" (DPSIR-CC) framework.

3.2.1. Literature Review

Although climate change has been identified as one of the most pressing issues for water governance, RBM policies in the European Union have not tackled those emerging challenges within the existing instruments for water quality monitoring.

Unlike other water policy instruments[6], the WFD does not explicitly address impacts on water bodies other than directly produced by anthropogenic activities (Annex II WFD). However, previous applications of the DPSIR model in water management classified the impacts of global warming on water bodies often as part of the component "pressure" within the DPSIR model (Pirrone et al. 2005; Kristensen 2004; EC 2003a). While RBM has prioritised the integration of climate change adaptation policy, marine science has been using the DPSIR methodology to categorise indicators of climate change within the framework. To study how climate change could affect the achievement of good environmental status within the EU Marine Strategy Framework Directive (MSFD) Elliott et al. developed the "DAPSI(W)R (Drivers-Activities-Pressures-State change-Impacts (on Welfare)-Responses)" to "describe an Impact on human welfare as an adverse change in the system" (2017, 29). By integrating "variability or direct climate change effects" (Elliott et al. 2015, 9) this model aims to manage a *force majeure*, which potentially poses a threat to achieving the goals of the MSFD (ibid).

Incoherent terminology in the context of the DPSIR on the one hand and the threat climate change could pose to the aquatic environment on the other hand has been widely discussed in marine science. Despite visible signs of climate change in freshwater ecosystems, RBMPs within the WFD has been taking solely a policy-integration shaped approach characterised by the lack of systematically integrating direct effects of climate change into river quality monitoring.

Since the adoption of the first RBMP in 2009 several initiatives by the European Commission (EC) and legally non-binding guidelines within the CIS had stressed the need to integrate climate change into RBMP. Based on the EC's *White paper - Adapting to climate change: towards a European framework for action* (2009), the Guidance Document n° 24 *River Basin Management in a Changing Climate* calls for including "important but physically remote, indirect or longer-term drivers of water body status" (EC 2009, 5) into the pressure-impact assessment.

Additionally, to the mainstreaming of climate policy, it is considered crucial to assess how climate change could "add or reduce the level of risk" (ibid, 44) the environment is already exposed to from anthropogenic pressures.

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[6] See: The Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks and the Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy

While the Guidance Document n°3 categorises climate change as “other anthropogenic pressure” (EC 2003a, 55), six years later, the CIS working group on climate change adaptation differentiates between “primary and secondary pressures” (EC 2009, 5). Primary pressures arise when changing climate conditions trigger direct impacts on the environment, while secondary pressures describe “indirect links to climate change due to societal responses” (ibid, 5). Despite acknowledging water quality parameters would be “sensitive to climate change” (ibid, 25) the Guidance Document n° 24 assumes that discerning climate change induced impacts from anthropogenic pressures would not be possible until 2027.

At the meeting about “The Future of the Water Framework Directive WFD” in 2018, European Water Directors highlighted that climate change could mainly influence the achievement of the WFD’s objectives. Furthermore, European Water Directors acknowledged that preparing RBM for post 2027 requires dealing with uncertainties inherent to long-term climate change impacts.

Unlike other water policy instruments[7], the WFD does not explicitly address impacts on water bodies other than directly produced by anthropogenic activities (Annex II WFD). In light of unprecedented challenges for water management, Dworak and Leipprand (2007) and Quevauviller (2011) stress the need to develop robust policy responses. Although uncertainties in climate projections exist, Dworak and Leipprand emphasise the need to include potential impacts of climate change in each stage of the RBM cycle (Dworak and Leipprand 2007, 7f). According to Quevauviller a “knowledge base and supporting research” (2011, 24) are crucial for building robust adaptation policies in RBM. To assess the “future development needs” of RBM, Carvalho et al. (2019) delivered recommendations based on the results from a questionnaire amongst 100 experts. Together with agriculture, energy, and urban planning, climate policy has been considered as one of the key policy areas in need for further integration into the WFD (2019, 1234). Consequently, the study found that integrating climate policy in water management, evidence-based decision making, and long-term planning are one of the most important areas to be improved in RBM (ibid,1235f).

In the common understanding that global warming could pose a risk to achieving the objectives of the WFD, stakeholders in European water policy consider climate change

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[7] See: The Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks and the Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy

adaptation and policy integration as key to managing emerging challenges in RBM (EC, 2009). Although strengthening the science-policy interface is equally considered crucial, at present, unlike in marine science, there are no similar intentions to reform the DPSIR framework within the implementation of the WFD.

Yet, the need to systematically integrate climate change into the pressure-impact assessment has clearly been recognised, since it accounts for potentially severe impacts on the aquatic environment. Therefore, robust responses for conservation and restoration of waters need to be informed by a structured assessment of their implications including potential impacts of climate change.

The following modification of the conceptual DPSIR model consequently aims to highlight that emerging challenges in RBM require taking a holistic, multidisciplinary approach, which supports policy making in coping with "diverse requirements and still provide realistic solutions" (Mateus and Campuzano 2008, 29).

3.2.2. The Driver-Pressures-State-Impact-Response-Climate Change Model

Figure 2 illustrates the DPSIR-CC model, a first step towards integrating climate change into water quality monitoring in RBM with the aim to systematically analyse cause and effect produced by the interaction between the different components of the system in water management.

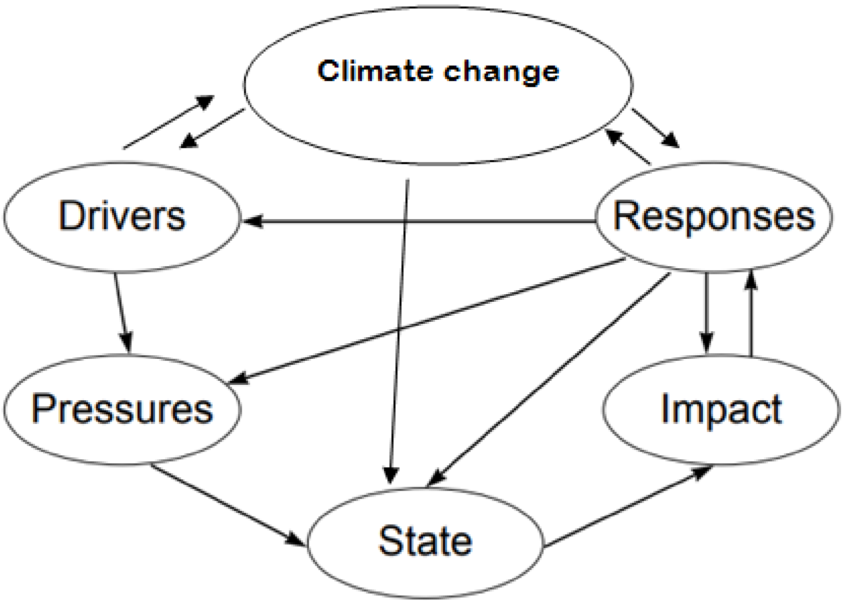

Figure 2 The DPSIR-CC model integrates climate change as a separate component, connected to drivers, state, and responses (Smeets and Wetering 1999, 6) [modified]

Figure 2 describes climate change as part of the DPSIR model with arrows indicating the linkages to drivers, state, and responses.

Climate change influences drivers if they react to changes in climate change mitigation policies and through adapting to changing climate conditions. Drivers could influence projected trends in atmospheric warming if anthropogenic activities, particularly those which reduce the emission of GHG, affect the presence of heat storing gases in the atmosphere. This explains why one arrow points towards the driver and another one points back to climate change.

Climate change directly influences the state of water bodies: The interaction between climate change and the component "state" depends on if and how the individual elements determining the state of a water body, e.g. hydrology, morphology, physicochemical elements, biological quality elements, react sensitive to changes in temperature and precipitation. This is subject to an in-depth analysis in the case study, see chapter 4.

Climate change influences response measures in water management: Atmospheric warming could impact the efficiency of restoration and conservation measures in water management in multiple ways.

Responses could affect climate change if water policy measures produce positive or negative effects on atmospheric CO_2 concentrations.

To put the framework to test, the following case study follows "the step-wise and cyclical approach" (EC 2009, 16) of the DPSIR framework as explained in chapter 3. To account for the direct effects of climate change on drivers and on the state elements, the case study is structured into the following steps:

In the first step, the identification of drivers analyses influences of climate change on human water activities; additive effects from anthropogenic pressures resulting from the drivers are illustrated by summing up and including the results from step one. Then, the link between climate change and state indicates that climate variables could affect the natural condition of water bodies directly. The subsequent impact assessment includes first the additive effect produced through drivers, which are subject to influences from climate change, and second, the direct effect of climate change on water body state elements.

As a result, the DPSIR-CC model demonstrates that climate change could produce impacts on each of the monitoring steps in RBM. As the cyclical approach enables a regular evaluation and the continuous review of measures, applying the DPSIR-CC for operational monitoring allows swiftly responding to climate induced changes in aquatic environments. This could enhance the understanding of and track changes attributable to short-term climate variability; regular assessment based on hydro-climatic models thus strengthens the role of science in providing a sound basis for policy decisions.

3.3. Climate Change, Climate Variables and the Hydrologic Cycle

To understand the complexity inherent in the functioning of the climate, this chapter provides an overview of the most important processes and projected changes, which determine the dynamics related to the quantity and quality of surface water. Based on the following information, the subsequent case study identifies climate variables relevant to applying the DPSIR-CC model.

3.3.1. Climate Change and the Hydrologic Cycle

Climate change, expressed as the change in climate conditions over time, results from climate variability and from anthropogenic GHG emissions. Climate variability describes alterations in climate conditions beyond the mean state, as consequences of natural processes, created from natural interactions of the climate's components or as a result from external forcing, such as anthropogenic activities.

Complex interactions of the Earth's systems components and feedback mechanisms, which either amplify or diminish the changes in climate conditions, complicate projection on the magnitude and direction of changes. Discerning those processes from the impact of existing anthropogenic pressures on the environment add to the complexity of climate projections. To systematically approach those challenges, the fourth report of the IPCC has defined three levels of uncertainties, namely unpredictability, structural uncertainty, and value uncertainty (IPCC 2005, 1). Unpredictability expresses the chaotic behaviour of systems, mostly in the realm of human behaviour or social systems. Structural uncertainty, which "tends to be underestimated by experts" (ibid, 1) refers to the lack of coherent structural approaches or incomplete frameworks. Value uncertainty addresses incomplete, missing information or data (ibid). When referring to the correctness of data or information, the

IPCC foresees a quantitative approach on structuring into very high, high, medium, low, and very low confidence (ibid, 3). Climate projections which provide information on potential implications for water bodies should hence be understood in light of different types of uncertainties.

3.3.1.1. The Hydrologic Cycle

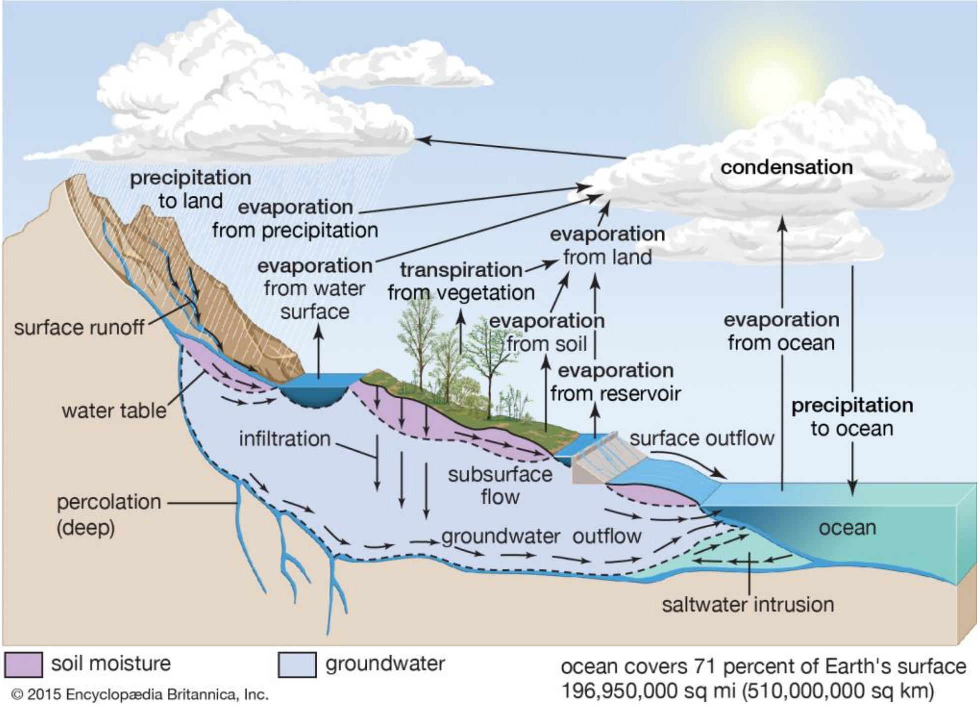

Figure 3 Description of the hydrologic cycle and the interrelation between its main components, evaporation, condensation, and precipitation (Encyclopaedia Britannica 2015)

Figure 3 illustrates the components, which determine the hydrologic cycle, namely precipitation, evaporation and condensation. Precipitation occurs on land and over oceans, water evaporates from soil and from natural as well as from artificial water bodies, runoff processes are present in surface, sub-surface, and groundwater. In clouds water vapour condensates and continues the water cycle with precipitation over land and waters.

Furthermore, figure 3 depicts that precipitation and runoff are interlinked processes, which strongly depend on multiple factors. Therefore, a thorough understanding of climate change impacts on rivers requires understanding how climate change impacts components of the hydrologic cycle. In the following an overview of projected changes in temperature and precipitation explains the links between the climate system and rivers.

3.3.1.2. Temperature Projections

The IPCC's synthesis report 2014 includes projections from four different emission scenarios, the Representative Concentration Pathways [8](RCPs), which project with medium confidence that between 2016 and 2035 the mean surface temperature will increase in the range of 0.3°C to 0.7°C relative to the period of 1986 to 2005 (IPCC 2014,10). Scientists using climate projections from three different RCPs, RCP 4.5, RCP 6.0, and RCP 8.5, consider it "likely" that by the end of the 21st century temperatures will exceed 1.5°C relative to the period 1850-1900. Medium confidence is attributed to projections indicating a rise in temperatures to more than 2°C until 2081-2100 (ibid, 60). With rapidly increasing atmospheric temperatures it is considered "virtually certain" that extreme temperature conditions, hot and cold periods are projected to appear more frequently and last longer (ibid, 10). Strongest increases in temperature are projected to occur in "tropical and Northern Hemisphere subtropical regions" (ibid, 11).

3.3.1.3. Precipitation Projections

While the trend of increasing near surface air temperature is projected to occur on a global level, changes in precipitation patterns could be rather heterogeneous. Based on the RCP 8.5 scenario, the IPCC's fourth assessment report concludes that wetter regions in mid and high latitudes as well as in the "equatorial Pacific" are "likely" to experience more precipitation; "subtropical" dry areas however will experience less rainfall (ibid,11). Heavy precipitation could bring "greater risk of flooding at regional scale (medium confidence)" (ibid, 8). Very high confidence it attributed to projections that more frequently occurring extreme weather events could render natural ecosystems and human activities vulnerable to slight changes in climate conditions.

3.3.1.4. Evaporation and Evapotranspiration

Evaporation, the cyclical process of the water transforming from solid or liquid state to water vapour and back to the initial state, occurs over land, oceans as well as over the cryosphere.

Energy needed to transfer water from one state of matter to the next comes from solar radiation, water vapour, and thermal conditions in the atmosphere. Air exchange, wind

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[8] RCPs represent possible scenarios describing "pathways in order to emphasize that they are not definitive scenarios, but rather internationally consistent sets of time-dependent forcing projections that could potentially be realized with more than one underlying socioeconomic scenario" (Collins et al.2013, 1045).

speed, and orography are additional factors influencing evaporation. As atmospheric temperature increases more energy is provided to the process; this enhances the production of water vapour, which in turn, speeds up the hydrological cycle. Water vapour, one of the most powerful GHG, influences the heat holding capacity of the atmosphere and is responsible for global energy distribution. The presence of clouds and solid water are strongly influencing the radiation budget in the atmosphere. Both containing the physical property of high albedo, surfaces covered with snow, ice or low clouds reflect most of the incoming solar radiation, thereby preventing the atmosphere to store heat.

Evapotranspiration describes two processes, evaporation and transpiration. Evaporation is an important component of the hydrological cycle, which depends on temperature and the presence of water. As mentioned previously, evaporation is the process which turns liquid or solid water into the gaseous state. Transpiration, the process of vegetation consuming moisture present in the atmosphere, is an "important component of the water, energy, and biogeochemical cycles" (Jia et al. 2017, 25). This process forms an essential link between the hydrosphere and the biosphere and influences soil moisture as well as surface water and groundwater.

3.3.2. Climate Change and Rivers

River flow is determined by the "seasonality of precipitation and temperature, as well as by catchment characteristics such as geology, soils and land cover" (EEA 2016a).

In addition to the direct effects which result from rising near surface temperature, changes in precipitation patterns and evaporation influence the thermal and hydrological regime of rivers. Therefore, it is crucial to understand how those climate variables interplay in the complex interaction of other factors influencing the water cycle.

3.3.2.1. Snow Melting and Glacier Retreat

Increasing temperatures and changes in precipitation patterns highly affect rainfall stored as ice and snow. Particularly in regions which depend on runoff from snow melting, river discharges are strongly affected by rising temperatures which alter the amount and timing of snowpack melting. Despite "some projected increases at higher altitudes" (Bates et al. 2008, 27), overall it is projected that the Northern Hemisphere could experience a decrease of 9 to 17% in the annual mean snow coverage until 2100 (ibid, 28). Additionally, global warming and alterations in rainfall patterns highly affect the water storage capacity of glaciers. As freshwater released by glaciers highly influences the river runoff downstream, there is a “critical link between the fate of glaciers and sustainability of water resources” (Mark et al. 2015, 184). Hence, by reducing the storage capacity of glaciers, climate change could produce irreversible effects on the interaction between cryosphere and hydrosphere.

Irrespective of alterations in the amount of rainfall, the effects of global warming and temporal shifts in snow and ice melting could produce severe impacts on “future water availability – predicted with high confidence and already diagnosed in some regions” (Barnett et al 2005, abstract).

3.3.2.2. Floods and Droughts

Regional climate projections show that heavy precipitation could increase thereby producing more frequently occurring high flow regimes. As extreme droughts are projected to reoccur more often and at a longer duration, particularly vulnerable regions in the “sub-tropics, low and mid-latitudes” could be severely affected (Bates et al. 2008, 3). Complex interactions between the components of the hydrological cycle determine river runoff in quantity, seasonality, and quality. While global atmospheric warming causes water temperatures to surge, heavy precipitation in winter coupled with snowpack melting produces floods. Low flow regimes and surging air temperatures during dry summer months could lead to rivers drying out altogether. To understand how interconnected processes could produce severe impacts on rivers, the functioning of the individual components of the hydrological cycle at the background of geological, climatic and topographic conditions of rivers need to be taken into consideration.

4. Case Study: Testing the Model and Evaluating its Functioning by the Example of the Durance River Catchment

This chapter applies the DPSIR-CC to water management in the Durance River catchment with the aim to evaluate the functioning of the framework and illustrate the importance of integrating climate change into RBM. Located in the south-eastern parts of the Rhône River Basin, the Durance, an“alpine-Mediterranean river” (Olivier et al. 2009, 284), drains a catchment of 14 322 km^2 (ibid).

4.1. Introduction: The Durance Catchment

The Durance River has its source close to the town Montgenèvre located at 2 459 m above sea level in the south-western Alps. As the 304 km long Durance River flows southwards, it is greatly influenced by variable conditions in geology, hydrology and climate (Encyclopaedia Britannica 2007). Its main tributaries are the Bléone and the Verdon River, both torrents originating in the southern Alps. As its slope gradually declines, the Durance River loses its alpine character until it flows into the Rhône River near Avignon at 16 m above sea level. Due to various factors which influence the river flow, the annual volume of river runoff fluctuates between 40m^3/s in dry years, while floods could carry up to 5000 m^3/s. The total annual volume of water carried by the Durance River could reach from 3 to 8 billion m^3 of water (Balland et al. 2002, 31f).
To consider the strong alterations in geology, hydrology, and climate, Magand divides the catchment into three different parts (2014, 31):
The upper area, *Haute Durance*, covers ¼ of the Durance catchment and is highly influenced by the alpine character of its source located at over 2000m above sea level (ibid, 37). Snowpack melting and increasing temperatures in spring produce peaks in river flows in the *Haute Durance* and monthly maxima at the *Moyenne Durance* in May and June (ibid,40). From its origin until the confluence with the Ubaye, the hydrology of the Durance River is governed by a nivo-glacial flow regime characterised by high amounts of snowmelt runoff in early spring (Olivier et al. 2009, 285).
The middle part, *Moyenne Durance*, is characterised by “subalpine” (ibid, 285) runoff patterns and flows from the multiple purpose reservoir Serre-Ponçon to the town of Mirabeau. In spring peaks in river flow carried by its headwaters feed the large reservoir Serre-Ponçon in *Moyenne Durance*. Due to the dry Mediterranean climate, low flows

occur in summer more pronounced in southern regions. Strongly affected by artificial channels, hydropower installations and multiple anthropogenic pressures on the water resources, the middle section of the Durance has lost its natural flow regime. After passing the reservoir Serre-Ponçon, most of the stream is diverted into canals, consequently reducing the flow to 2 to 5 m^3/s, which corresponds to 1/40 of its natural flow (ORRM-PACA n.d.).

The downstream area, *Basse Durance***,** starts at the town Mirabeau and reaches until the confluence with the Rhône River situated close to the city of Avignon. As it approaches the Mediterranean Sea, the slope of the Durance River decreases significantly until it reaches its lowest point at 13 m above sea level close to the Mediterranean coast (Magand 2014, 37). The Mediterranean river sections experience high flows in November and December, typically resulting from storms and extreme precipitation events (Magand 2014, 40).

As diverse is its hydrology, as heterogeneous are the climatic conditions which influence the characteristics of the Durance River.

Altitude and distance to the Mediterranean coast correlate with climate conditions, as the alpine landscape in *Haute Durance* experiences precipitation mostly in form of snow, whereas the Mediterranean climate downstream in *Moyenne* and *Basse Durance* is characterised by low amount in rainfall in summer and liquid precipitation in winter (Magand 2014, 39). In northern areas of the catchment winter temperatures are regularly decreasing to below freezing point, while in Mediterranean parts of the basin liquid precipitation occurs due to higher atmospheric temperatures during winter months (Sauquet et al. 2015, 38).

4.2. Climate Projections for the Durance Catchment

In the following, the results from Magand (2014), Sauquet et al. (2015), and Sauquet and Andrew (2017) provide an overview of projected changes in temperature, precipitation, and river runoff.

Uncertainties related to the modelling are classified according to Magand (2014) into three different types: 1. Uncertainties stemming from projections of radiative forcing, which depend on socio-economic activities, 2. Uncertainties from climate models due to errors or incomplete knowledge about physical processes, occurring in climate models, downscaling, and hydrologic models, 3. Uncertainties, which result from the variability of internal climate processes and the chaotic property of the climate system (2014, 23f). Sauquet et al. (2015) use projections made by Magand (2014), hence the models developed are subject to similar types of uncertainties. Consequently, the interpretation of the following data should be understood considering uncertainties inherent in the projections.

4.2.1. Temperature Projections

Regional climate projections show a uniform increase in average temperature by approximately 1.0°C for the entire Durance River Basin (Sauquet et al. 2015, 107; Magand 2014, 193). In summer, atmospheric temperatures are expected to rise by about 2.1 °C, while during winter the increase is projected to be less pronounced, approximately 1.4°C (Magand 2014, 193). Potential evapotranspiration, influenced by water vapour, wind velocity net radiation and temperature, is projected to increase uniformly within the Durance catchment up to 66 mm/year (7%) (ibid, 197).

4.2.2. Precipitation Projections

Regional climate models project a reduction in annual precipitation reaching from -21% to +13% with an overall average of -4%. This corresponds to -225mm/year (-21%) or +134 mm/year (+13%) (Magand 2014, 193).

Precipitation patterns are expected to strongly vary in season and spatial distribution. During summer months a clear decrease is projected, while in winter, no significant alterations in rainfall are expected (ibid, 195). In *Basse Durance,* where dry Mediterranean summers already affect water availability, climate models show a clear decrease in precipitation, which is projected to occur pronounced in summer (ibid).

4.2.3 River Flow Projections

Atmospheric warming strongly affects river flow regimes, fed from water stored in the cryosphere. As its source is located at over 2000 m above sea level, runoff from solid precipitation highly influences the amount and timing of the Durance River flow regime. If temperature trends affect the storage capacity and snow cover duration in alpine regions, volume and timing of the river runoff downstream change.

The following projections on hydrological changes based on 300 climate models clearly show a strong decrease in river flow for the Durance catchment (Magand 2014, 197f). In total, climate projections converge in projecting a decrease of river runoff influenced by a strong reduction of the annual snowpack storage capacity up to -25%. As a result of a reduction in the duration of snow cover, changes in the amount and timing of runoff are projected. Snow melting could shift to December, January and February causing peaks in river flow to occur about one month earlier than presently (ibid, 201).

This is in line with Andrew and Sauquet, (2017) projecting changes for 2050 with the reference period 1980-2009.The results show that overall alterations in river flow regimes could cause significant alterations of water budgets in the upstream area of the Durance River. Earlier melting of snow in mountainous areas due to a reduction in the duration of snow cover and less volume of solid precipitation in winter cause a trend of decreasing river flow projected up to -15% and a temporal shift in the peak seasons of high flows in spring (AIR, 2017; Andrew and Sauquet 2017, 7).

4.2.4. Overview of Projected Climate Trends

Overall, the results of different climate projections for the Durance catchment until 2050 show the following trends, providing the information relevant to the analysis of climate trends, which influence the individual components of the DPSIR-CC model:

- Increasing atmospheric temperatures, 1°C in average up to over 2°C during summer months, could severely influence the hydrologic cycle.
- River runoff fed from snow melting are particularly vulnerable to atmospheric warming since alpine areas are projected to experience a significant decrease in snow storage capacity (up to -25%).
- Despite regional and seasonal variations, an overall decrease in precipitation is projected.
- The most pronounced changes in temperature and precipitation are projected for Mediterranean regions, which are already facing water stress aggravated during heat waves in summer.

Resulting from the strong alterations in atmospheric temperatures and its predisposition with already limited water resources, the Mediterranean region has been identified as a “hot spot” in many climate model projections, with increasing temperatures and decreasing winter precipitation (Giorgi 2006, 2).

4.3. Identification of Anthropogenic Drivers

The sub-catchment of the Durance River at the reservoir Serre-Ponçon is located partly in *Moyenne Durance* and partly in *Basse Durance*, where on the one hand anthropogenic influences highly modified the natural water course and on the other hand water availability is strongly affected by the dry Mediterranean climate. Downstream of the Serre-Ponçon reservoir a network of artificial canals diverts parts of the natural river flow to serve different water use purposes. Irrigated crop cultivation, hydropower production, industry, and tourism/leisure are the main anthropogenic activities, which depend on the availability of surface water from the Durance River.

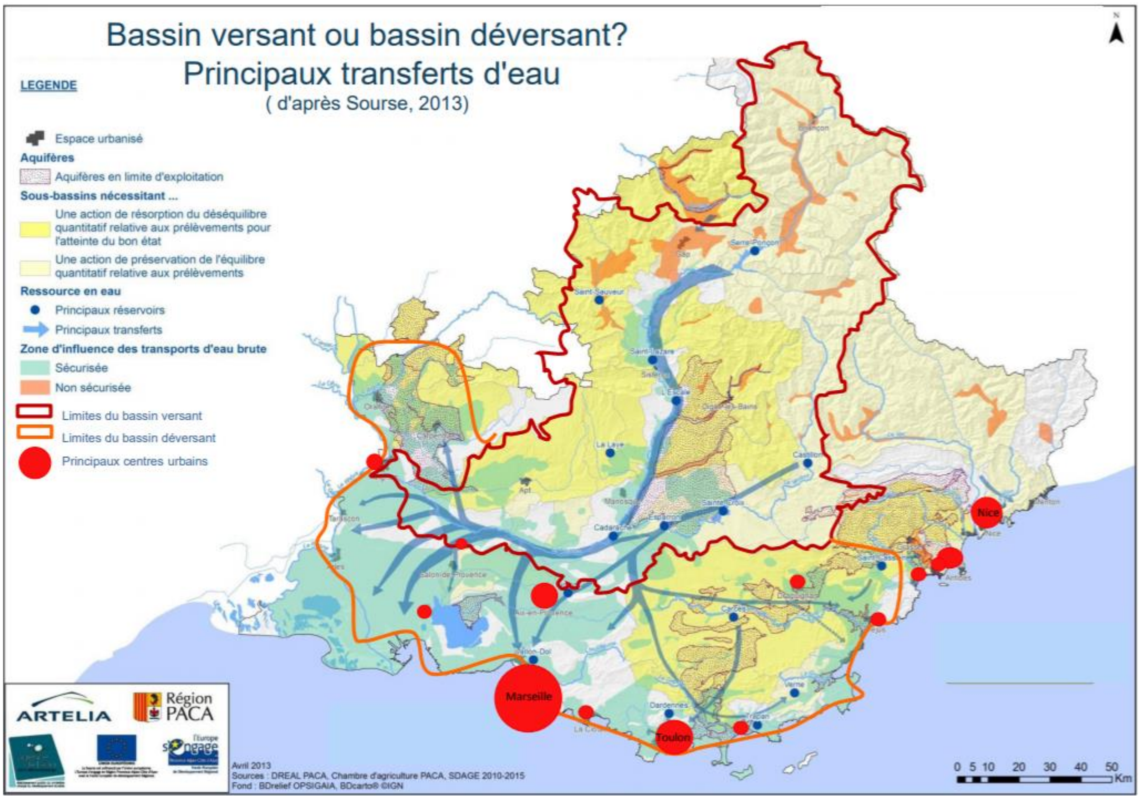

Figure 4 The distribution of water in the Durance catchment for multiple purposes (Sourse 2013, cited in AIR 2017, 43)

The figure shows the Durance catchment around the Serre-Ponçon reservoir. The blue lines illustrate the main routes downstream through which the multipurpose reservoir supplies the *Basse Durance*. The areas shaded in yellow indicate that water abstraction is regarded as a significant pressure and response measures to restore the quantitative equilibrium are needed. Green triangles, predominantly present in *Basse Durance*, illustrate where irrigated agriculture abstracts water supplied by artificial canals downstream the Serre-Ponçon reservoir.

4.3.1. Irrigated Agriculture

The construction of reservoirs and canals for agricultural irrigation in the Durance River dates to the Middle Ages. In the 18th and 19th century the network of dams and reservoirs was expanded in order to manage the strong variations in river flow and serve multiple human water uses (Aspe et al. 2016, 156).

With the expansion of the gravity-fed irrigation network agricultural sectors experienced a transformation into large scale cultivation consuming the share of water abstracted (Balland et al. 2002, 31).

4.3.2. Domestic Water Demand

In 2012 the Durance catchment counted more than 5 million inhabitants (Sauquet et al. 2015,50). Population growth has not been developing homogenously throughout the catchment area. The northern parts of *Haute Durance* are characterised by a rural, less densely populated land with the lowest population growth rate of the region, 1% growth since 1962 (ibid). In *Moyenne Durance*, the annual growth rate amounts to 1.7%, in *Basse Durance* it remains at around 1.35% since 1999. Water is used for domestic purposes to satisfy water demand for hygiene, sanitary purposes, household uses, cooking purposes and drinking water demand (ibid, 53).

4.3.3. Industry and Tourism

Industry: Water is used for the entire production chain, including fabrication, cooling, heat transfer, cleaning of machines, and waste treatment.

In the *Basse Durance* the largest water consumers are chemical factories, refinement, metal industry, paper factory, and steel production. In the Durance catchment, industries abstract surface water mainly for cooling purposes and discharge 93% back to the environment (Sauquet et al. 2015, 55f).

Tourism: The region has experienced a rapid increase in touristic infrastructure, which intensified the pressure on land, water, and energy supply. Peaks in water demand during summer months in the south and during winter in northern alpine areas puts further pressure on natural resources. Considering that the Durance river flow is highly dependent on water supplied from mountainous regions, the consumption of water for artificial snow production influences the water budget in downstream areas of the catchment. Water for artificial snow production is either abstracted from natural surface water bodies or from drinking water supply networks (Sauquet et al. 2015, 55f). In the Mediterranean regions of the Durance catchment, surging water demand for golf course irrigation consumes high amounts of the freshwater resources. Therefore, the following analysis understands water abstraction for golf course irrigation and artificial snow production as main indicators for the driver “tourism and leisure”.

4.3.4. Hydropower production

The two largest reservoirs in the Durance catchment are Serre-Ponçon with the capacity of 1030 million m^3 at the Durance River and Sainte-Croix with 301,5 million m^3, at the Verdon River (Kuentz 2013,35). Together, they account for 94% of the storage capacity for hydropower production in the Durance catchment (Sauquet et al. 2015, 30).
Serre-Ponçon, the largest reservoir, mainly influences the river flow of the Durance by supplying a 250 km long network of canals, which serves gravity-fed irrigation in agriculture, hydropower production, and river flow regulation purposes.
Downstream the reservoir 17 dams and 32 hydroelectric power stations are operating at a total installed power of 2000 Megawatt (MW) (ibid, 45). Hydropower production is the second most important energy source in Frances and crucial for the Durance catchment generating 50% of the regional electricity to supply more than 2,5 million inhabitants of the region Provence Alpes Côte d’Azur (edf, 2016). Due to the ability to ramp-up its operation from 0 to 100% in less than 10 minutes, hydropower installations are used as supply peaks in electricity demand, particularly in winter, while nuclear power installations are operating to cover the base-load in electricity demand (Sauquet et al. 2015, 5; ibid, 45).

4.4. Climate Change Mitigation and Climate Change Adaptation Versus Drivers

This chapter evaluates if and how climate change mitigation policies and/or climate change adaptation influence the anthropogenic drivers of water use identified in chapter 4.3.
The following table addresses two questions regarding of the anthropogenic water uses:

- Do climate change mitigation policies influence the driver?
- Does climate change adaptation influence the driver?

Table 4. 1 The influence of climate change mitigation policies and climate change adaptation on drivers of water use

Climate change		Mitigation	Adaptation	**Total**
Drivers	Hydropower	+	+	2+
	Agriculture (irrigation)		+	+
	Industry (cooling)	+	+	2+
	Tourism/leisure (golf course irrigation, snow production)		+	+
	Domestic water demand			

Hydropower production: On the one hand, electricity production from hydropower is projected to face constraints as a result of decreasing water availability in the Durance catchment, + (European Water Movement 2017). On the other hand, it is already the most important source for renewable energy production in the Durance catchment and promoted by national climate policies aiming to curb emissions from the energy sector, + (France 2018, 23f).

Irrigated agriculture is highly climate-sensitive since projected warming in the Durance catchment leads to a decrease in water availability, which impacts crop cultivation. To adapt to those changes, water demand for irrigation could increase, +. Other factors, such as changes in the type of crops or technological solutions, which could alleviate the impacts, are not subject to an in-depth analysis in this case study. Climate change mitigation actions, namely biomass cultivation, plays a minor role in the agricultural sectors of the Durance catchment, as, overall, the surface of agricultural land-use has decreased due to urbanisation trends, particularly in coastal zones (Sauquet et al. 2015, 49).

Industrial water use in the Durance catchment primarily serves cooling purposes (ibid, 55). If, at higher atmospheric temperatures, the water temperature increases, the sector adapts by abstracting more water, +. Climate change mitigation plays a role in the industrial sector, +, France’s national low-carbon strategy aims to reduce greenhouse gas emission from the industrial sector by 75% by 2050 compared to the reference scenario in 2013 (France 2018, 18).

Tourism and leisure are both sectors sensitive to changes in atmospheric temperature, since mountainous regions of the catchment use water to produce artificial snow. In southern areas of the Durance River golf course irrigation is the predominant water use in tourism and leisure. Irrigation practices adapt by abstracting more water, as water demand for plant growth increases. Climate change impacts artificial snow production twofold. First, global warming is projected to affect the snowpack storage capacities in the Alps; consequently, skiing resorts will need to compensate losses in natural snow cover and abstract more water to produce artificial snow, +. Second, an overall reduction in the availability of water resource additionally impacts water use for artificial snow production. The latter becomes relevant once the impact on water bodies has been identified and policy response measures are being developed. Tourism and leisure, both sectors are not mainly influenced by climate change mitigation in the Durance catchment.

Water use for domestic purposes depends primarily on population growth, technology and socio-economic factors; changing climate variables play a minor role.

4.5. Anthropogenic Drivers and Directly Resulting Pressures

Table 4.2 describes the connection between anthropogenic activities, which directly result into pressures exerted on the aquatic environment in the Durance catchment.

Table 4. 2 The relationship between anthropogenic drivers and the directly resulting pressures

Drivers / **Pressures**	Agriculture (irrigation)	Hydropower production	Domestic water demand	Industry (cooling water)	Tourism/leisure (irrigation, snow production)	**Total**
Water abstraction	2+	3+	+	3+	2+	11+
Morphological changes		3+				3+
Hydrological changes		3+				3+
Thermal pollution				3+		3+

The choice of anthropogenic pressures included in the analysis is determined by the nature of human water use identified in chapter 4.3 for each driver. Therefore, agriculture accounts only for quantitative water use, e.g. irrigation, which results in water abstraction; although diffuse source pollution, typically originates from agricultural practices, it is outside the scope of this analysis. Industrial sectors in the Durance catchment use water mainly for cooling purposes, therefore thermal pollution and water abstraction are included, while point source pollution is not part of the case study.

Water abstraction: Agricultural irrigation, 2+, hydropower production, 3+, domestic water demand, +, industry for cooling purposes, 3+, and tourism/leisure for irrigation of golf courses and snow production, 2+, are the main anthropogenic activities, which abstract surface water from the Durance catchment. In the last decade, about 30% of surface water directly abstracted was used for agricultural irrigation and the watering of plants for private and public purposes. According to Sauquet et al. in average, 6% were destined for industry and tourism/leisure respectively, 14% for domestic and public water demand, and 50% served for the functioning of gravity fed channels. In terms of spatial distribution, freshwater was predominantly abstracted in the southern regions of *Basse Durance*, where large artificial canals supply multiple water uses. 12% of the total amount originated in Moyenne *Durance* and 5% in *Haute Durance*. Despite less than 25% of the water abstracted is consumed, water supply to large urban areas outside the catchment explains why not even half of the water resources are returned to the natural flow of the Durance River (2015, 58f). Causing a reduction in river flow, water abstraction could be subsumed under hydrological changes. However, the fact that large amounts of water are “exported” to areas outside the catchment requires taking into account quantitative water use, namely water abstraction, separately. In addition to that, with regards to assessing potential implications of climate change, chapter 2 of this thesis outlines the advantages of analysing water abstraction as an individual component.

Morphological and hydrological changes: Hydropower production and gravity-fed agricultural irrigation are primarily responsible for altering hydrology, 3+ and morphology, 3+ of the Durance River. With the construction of dams, weirs, and reservoirs for hydropower production the natural river flow regime has significantly changed; artificial channels and floodplains serve to attenuate high flows, however producing severe consequences for the aquatic environment. The construction of the large channel system downstream of the Serre-Ponçon reservoir has altered the natural width and depth of the Durance River. By diverting 90% of the natural flow into artificial channels, the river flow is reduced to 2 m^3/s, which corresponds to 1/40 of the natural volume flow (Warner 2012, 38). Interruptions of natural connections of water bodies and habitat loss are amongst the consequences resulting from the construction of dams and artificial floodplains. In addition to that, barrages hinder water from moving and impact sediment transport and the aquatic fauna (ibid, 39).

As mentioned in chapter 4.3, the Serre-Ponçon reservoir operates when energy demand is at its peak. Consequently, hydropeaking defined as “the discontinuous release of turbined water due to peaks of energy demand” (Greimel et al. 2018, 91), causes rapid changes in river flow regimes. Intermittent high and low flow regimes downstream the reservoirs impact sedimentation levels and trigger fluctuations in water temperature conditions (ibid, 100).

Thermal pollution results from the discharge of water at warmer temperatures due to water use for industrial cooling purposes, 3+. The largest share of water abstraction for industrial use occurs near urbanised areas in *Basse Durance*, where two of the largest chemical and pharmaceutical companies strongly rely on the water resources carried by the natural Durance River as well as by the artificially constructed canals. SANOFI, a pharmaceutical company, located in Sisteron, *Basse Durance*, abstracts water from the artificial canal operated by Électricité de France (edf) and discharges it back to the Buëch River upstream its confluence with the Durance River (DRIRE Provence-Alpes-Côte D’Azur 2010, 23). The petrochemical production plant of ARKEMA discharges water used for cooling purposes into the artificial Manosque canal, which is supplied by natural water from the Durance River in *Moyenne Durance* (ibid).

By summing up the values “+” attributed to the pressures from each driver, table 4.2 shows that water abstraction, 11+, is strongly influenced by climate change and at the same time severely impacting the Durance River.

4.6. Direct Effects of Climate Change and Pressures on the State of the Surface Water Body

Integrating the results obtained in the previous analysis, the following table illustrates the additive effect of climate change and anthropogenic pressures, which directly impacts the components of surface water state.

Table 4. 3 Direct effects of climate change and existing pressures on state elements of surface water bodies

State		Direct impact: CC[9]	Pressures				Total
			WA[10]	MC[11]	HC[12]	TP[13]	
Hydrology	Water level and discharge	+	11+		3+		15+
	Minimum flow	+	11+		3+		15+
River continuity					3+		3+
Morphology	Bank dynamic			3+			3+
	Riverbed structure			3+			3+
	Riverbank vegetation	+		3+			4+
Physicochemical elements	Temperature	+			3+	3+	7+
	Oxygen balance	(+)					(+)
	Salt content						
	Acidification	(+)					(+)
	Nutrient content	+					+
Chemical status	Substance concentration	+	11+			3+	15+

Hydrology: Climate change directly impacts water level and discharge as well as the minimum flow of rivers, +.

Sauquet et al. (2015) worked with the results obtained by Magand (2014) and included changes in maximum snow storage capacity and evapotranspiration to simulate projections for the Durance runoff at Serre-Ponçon for the period 2036 to 2065 referring to 1980-2009. For the Durance River at the Serre-Ponçon reservoir, the present annual flow (76 m^3/s) is projected to decrease by -7.2 m^3/s, which implies a reduction of the present annual flow regime by 10%. High flows in May and June, which presently carry 144.9 m^3/s, could decrease by -15.5 m^3/s. This corresponds to a reduction of the present

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[9] Climate Change
[10] Water abstraction
[11] Morphological changes
[12] Hydrological changes
[13] Thermal pollution

river flow of approximately -11%. During the dry summer months, June to August, low flow, which carry 70.1 m^3/s in average, are projected to experience more pronounced changes, namely a decline of -14.8 m^3/s, which corresponds to 21% less volume flow (Sauquet et al. 2015, 235).

Anthropogenic pressures such as water abstraction, 11+ and hydrological changes, 3+, strongly impact water level and discharge as well as minimum flow by altering the water flow rate, while physical barriers constructed for hydropower production affect the **continuity** of the Durance River, 3+.

River morphology is strongly impacted by changes stemming from the construction and operation of hydropower installations and the diversion of large amounts of the natural stream into a large network of artificial canals downstream the reservoir, 3+. Riverbank vegetation reacts to changes in air temperature and precipitation patterns, +.

Physicochemical elements: Temperature is sensitive to changes in atmospheric temperature, +, thermal pollution, 3+, and fluctuations in flow regimes, 3+. Oxygen balance and acidification, which react to direct or indirect changes in temperature conditions, are not analysed in detail due to the complex interaction with other factors.

The chemical status of surface water bodies, indicated with the concentration of priority substances according to the EQSD, changes if global warming affects water temperature conditions, +.

Chemical status: Water abstraction impacts the concentration of substances by decreasing the amount of water in which substances are diluted, 11+, while thermal pollution could change the composition substances, since elevated temperature conditions enhance chemical reactions, 3+.

4.7. Potential Consequences for Hydropower Production

To understand how changes in water body state elements potentially create constraints for hydropower production, this chapter first identifies the state element, which determines the functioning of the hydropower reservoir in the Durance catchment. The artificial lake at Serre-Ponçon supplies a large network of artificial canals for multiple purposes and controls the natural flow of the Durance River. In spring, the storage is naturally recharged with the inflow from snowmelt carried by the *Haute Durance*. In summer, the reservoir supplies water at low flow regimes in the downstream section of the Durance River to alleviate the pressure on the water resources and provide water for agricultural irrigation. In autumn, water is stored to meet peaks in energy demand in winter (Branche 2015, 77).

The storage capacity of the multipurpose reservoir hence relies strongly on the amount and timing of volume flow carried by the headwaters of the Durance River.

Table 4.3 illustrates that components of the hydrological state, directly influencing the functioning of a hydropower plant (e.g. Mukheibir 2013; Ciscar and Dowling 2014), are at the same time subject to strong impacts from climate change as well as from anthropogenic pressures in the Durance catchment, 15+.

As described previously, hydrologic models show an overall decrease of annual river flow volume up to 10%. In addition to the temporal shifts, the runoff is projected to decrease by -11% in spring and -21% in summer (Sauquet et al. 2015, 235).

This allows concluding, that the operation of hydropower installations in the Durance catchment could be strongly affected by a reduction in the amount of river flow as well as by temporal changes of runoff.

If the volume flow decreases by 11% in spring, the storage capacity for peaks in demand during summer months is negatively influenced. A decline in river flow during summer (-21%) exacerbates water shortages during dry periods; consequently, reduced water storage capacity limits the potential to meet peak electricity demands in winter (ibid). Additionally, if the runoff peak of snowpack melting occurs earlier in spring, the water carried downstream to the *Moyenne Durance* would limit the flexibility in generating hydroelectricity (Andrew and Sauquet 2017, 11). This analysis only includes changes directly resulting from climate change induced alterations of hydrology in the Durance catchment. In addition to that, the values in table 2.3 illustrate that existing anthropogenic pressures, which in turn are influenced by climate change, could put additional constraints on the amount and timing of water available for the operation of hydropower installations.

4.8. Potential Impacts on Ecological and Chemical Status of Surface Water Bodies

This chapter is based on the previous steps in the case study and applies the DPSIR-CC model to analyse how changes in the state of the water body could create consequences for the achievement of the WFD’s goals.

4.8.1. Introduction

Strong alterations in hydro-morphological conditions are underlying causes for the classification of the Durance River as Heavily Modified Water Body (HMWB).
In the following, a brief overview explains the main differences in determining the status of HMWB and the goals the WFD sets for those water bodies.
Article 4.3WFD foresees that for HMWB less stringent obligations than achieving good ecological and chemical status apply, provided that certain conditions are fulfilled. First, the change in the surface water results from physical alterations caused by human activity. Second, the water body is designated under Annex II, according to Article 4.3 WFD. And third, according to Article 4.3a WFD, the physical alterations caused significant hydro-morphological changes, which result into physical alterations of the water body (EC 2003b, 13).
For HMWB, the identification of the water quality status is undertaken in accordance with Annex V, Table 1.1 WFD, which specifies the quality elements used for the status assessment (ibid, 3). Similar to the classification of ecological status, the assessment of the ecological potential is based on comparing the degree of anthropogenic alteration to a reference condition, here the maximum ecological potential, it could achieve given the constraints imposed upon it by those heavily modified or artificial characteristics necessary for its use (ibid, 100).

4.8.2. Identification of the Current Ecological and Chemical Status

In the following, data from the river section “La Durance du Coulon à la confluence avec le Rhône” serves as an example for the water quality status of the Durance River downstream of the reservoir Serre-Ponçon. By taking data from one section of the river as illustrating example the subsequent impact assessment still provides an overview of potential consequences for water quality in large parts of the Durance catchment, since significant pressures resulting from hydropower production and agricultural irrigation in the *Moyenne Durance* and *Basse Durance* are predominant causes for not achieving Good Ecological Potential (GEP).

In 2018 the water quality status of the Durance River near the confluence with the Rhône was classified as moderate ecological potential. The chemical status of the surface water body was at good status (eaufrance 2018).

At the first deadline set in 2015, this section of the Durance River did not achieve GEP. The exemption applied to the non-achievement of the WFD's goals in 2015 was based on Article 4.4 to 4.7 WFD. Accordingly, it was explained that due to natural conditions restoring hydrological and morphological state from impacts on the vertical and longitudinal river profile would take more time than the deadline foreseen in the WFD (eaufrance 2015a).

The columns in table 4.4 describe the elements which determine the state of the water body, the pressures according to the information from table 4.3, the current state of the water body as reported by river basin management authorities for 2018, and impacts resulting from a change in the state element.

Table 4. 4 The state components of the surface water body, the pressures including direct effects of climate change, impacts on biological quality indicators resulting from changes in the state, and the current status of the water body

State		**Results from table 4.3** (Pressures and Climate Change)	**Impact on BQE** (diatoms)	**Current Status**
Hydrology	Water level and discharge	15+	(✓)	Moderate
	Minimum flow	15+	(✓)	
River continuity		3+	(✓)	
Morphology	Bank dynamic	3+	(✓)	
	Riverbed structure	3+	(✓)	
	Bank vegetation	4+	(✓)	
Physico-chemical parameters	Temperature	7+	✓	No data
	Oxygen balance	(+)	✓	High
	Salt content			Not included
	Acidification	(+)	(✓)	Good
	Nutrient content[14]	+	✓	High
Chemical	Substance concentration	15+	✓ Exceedance of thresholds (EQSD)	Good

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[14] This includes nitrogen and phosphorous

Hydrology: Climate change, water abstraction and hydrological changes affect water level and discharge as well as minimum flow, 15+.

River continuity is affected by hydrological changes, 3+.

Morphological state elements are reacting to morphological changes, 3+; furthermore, riverbank vegetation is sensitive to changes in temperature and precipitation, 4+.

Physicochemical elements: Elevated water temperature could result from global warming, strong fluctuations in water levels, and from thermal pollution, 7+. For the impacts on oxygen balance, (+), acidification, (+), and nutrient content, +, see Chapter 4.8.4.

Water quality is affected if atmospheric temperature levels change, if anthropogenic activities reduce the amount of water, and if water is discharged at elevated temperatures, 15+.

The **current status** of the water body shows for hydrological and morphological quality elements a moderate state, while physicochemical parameters are either classified at good or high status. The chemical status of the water body is classified as good (eaufrance 2018).

4.8.3. Identification of the Most Vulnerable State Element

By comparing the current quality status to the impacts on each of the state elements, table 4.4 illustrates which elements could influence achieving good ecological potential. Considering that hydrological state elements are at moderate status and existing pressures put additional constraints on hydrology, 15+, the following risk assessment assumes that the deterioration of biological quality elements could mainly stem from alterations in the hydrological regime. This is supported by the fact that the Durance catchment is already vulnerable to quantitative changes in the water budget, since for water resources in the Mediterranean climate it is projected that “effects of increasing or decreasing precipitation are greatly amplified in those catchments with the lowest runoff coefficients”(Goudie 2006, 387).

In line with propositions made by the CIS Guidance Document n°31, the following approach is based on analysing parameters for monitoring, which are “indicative of the biological and hydromorphological quality elements [and] most sensitive to the pressures to which the water body is subject” (EC 2015, 46).

4.8.4. Impact Assessment

Biological quality elements are particularly vulnerable to climate change, since most aquatic species "have limited abilities to disperse as the environment changes" (Woodward et al. 2010); slight changes in water temperature or flow conditions could severely affect the abundance and composition of phytoplankton, macrophytes, phytobenthos, benthic invertebrate fauna, and fish. Changes in natural conditions could lead to alterations in composition and/or abundance of species, reduce or increase biomass production, affect the lifecycle and/or metabolism, or the habitat of BQE. Since alterations in river flow regimes are triggered by climate change as well as by pressures resulting from human water uses, the following assessment analyses in detail potential implications of changes in hydrology for the achievement of GEP. This approach highlights the fact that the water body is already at moderate state due to hydro-morphological pressures and restoring natural flows have already been subject to response measures (e.g. Beche et al. 2015).

Therefore, it is important to investigate in detail how impacts of climate change on hydrology exacerbated by existing anthropogenic pressures could affect BQE.

In France, diatoms, a group of phytoplankton, are used to assess the quality of rivers. The Biological Diatom Index (BDI), a standardized method, covers a wide range of diatom species sensitive particularly to physicochemical quality parameters.

Altered conditions in light, temperature levels, acidification levels, toxicity, or nutrient content in the water body could strongly impact the composition and abundance of phytoplankton. In the following, the values in table 4.4 serve as an input to analyse how BQE are influenced by the state elements which themselves are subject to existing pressures and direct effects of climate change.

Light conditions for photosynthesising diatoms depend on the transparency of water. Hydrology, 15+, and temperature, 7+, indirectly affect water transparency through changes in water temperature, a process which intensifies at low flow regimes. Warm water conditions, the presence of sunlight, nutrients and CO_2 stimulate phytoplankton bloom. Additionally, Warner (2012) has found that hydro-morphological alterations caused by "long-profile barrages [which] trap fine sediments and nutrients, [promote] aquatic vegetation and blooms" (ibid, 39). Excessive algae growth, a characteristic sign of eutrophication, consequently, reduces the transparency of water and creates light-limiting conditions.

Acidification, (+), is not subject to a detailed analysis in this case study. Photosynthesising diatoms react to changes inCO_2, sunlight and nutrients. However, the uptake of atmospheric CO_2, in freshwater systems (Weiss et al. 2018) could influence the growth of diatoms.

Temperature conditions, 7+, are changing with thermal pollution, hydrologic alterations and are directly correlated with climate variables, 15+. Water temperature conditions determine chemical and biological processes and influence the growth rate of diatoms (Montagnes and Franklin 2001). Since water temperature and near surface temperatures are closely correlated, atmospheric warming strongly influences changes in temperature conditions of rivers. Furthermore, it was found that 25% of the increase in water temperature results from the reduction in flow (AIR 2017, 13). This indicates that, additionally to increasing near surface temperatures and thermal pollution, 7+, low flow regimes 15+ are strongly influencing water temperature levels, which in turn, impact the growth rate of diatoms.

Nutrient content: Nitrogen and phosphorous are limiting factors for phytoplankton growth. Low flow regimes, 15+ and warmer water temperatures, 7+, could promote the mobilisation of phosphorous (e.g. Whitehead et al. 2009), while floods, typically occurring in autumn, could enhance the leaching of nitrogen from agricultural soils. Despite uncertainties inherent in climate projections, Jeppsen et al. state that higher levels of nutrient concentration in surface waters located in Mediterranean climate zones predominantly result from enhanced evaporation (2011,17).Additionally, higher water temperatures and lower concentrations of oxygen in surface water could enhance the mobilisation of phosphorous present in riverbeds (Arnell et al. 2015, 107).

At the presence of CO_2 and sunlight, the mobilisation of nitrogen and phosphorous promote the bloom of phytoplankton

The production of toxic substances is influenced by water temperature conditions, 7+ and the concentration of substances present in water bodies, 15+. Factors influencing water temperature levels have been subject to discussion in the preceding paragraph. Substance concentration in turn depends on temperature conditions and the dilution capacity of a water body, which is determined by the volume flow. Diatoms strongly react to changing concentration in organic and chemical substances by shifting particularly the composition of species (Rimet 2012, 13). In addition to that, diatoms are strongly correlated with the **oxygen balance** in surface waters. On the one hand, anoxic waters present unfavourable conditions for most biologic organisms; on the other hand, at the presence of growth enhancing factors, phytoplankton bloom favour deoxygenation. Furthermore, various factors such as surging water temperatures, 7+, coupled with low flow regimes, 15+, depth, geology and topographic characteristics influence changes in oxygen balance.

The results clearly demonstrate that hydrology and water temperature are likely to impact several factors determining the natural condition of the Durance River. As a result of those changes in state elements, diatoms, the BQE used for the water quality assessment, could alter in composition and abundance.

The information from table 4.4 illustrates that elevated water temperatures, 7+, and hydrological alterations, 15+ could produce overall an additive effect resulting in a total of 22+ on nutrient content, temperature conditions, and substance concentration in surface water bodies. Light conditions are indirectly affected by hydrology, 15+, and temperature conditions, 7+. Changes in the pH of surface waters depend on multiple other factors directly and indirectly produced by climate change and anthropogenic pressures.

The results allow the conclusion, that despite BQE being classified at high status in 2018, changes in temperature, substance concentration, and light conditions, all three determining abundance and composition of diatoms, could deteriorate the current biological quality status. Consequently, this could pose a threat to the achievement of GEP. Additionally, the hydrological status, currently classified as moderate, could be severely affected by climate change as well as by existing anthropogenic pressures, 15+.Restoration measures aiming to improve the current moderate state hence need to account for changes resulting from direct impacts of global warming (state-climate change) as well as from human water use, which itself is influenced by climate change (drivers-climate change). Although not assessed in detail, the present chemical status could be subject to changes considering that multiple pressures on water quantity, 15+, and water temperature levels, 7+, trigger changes in the concentration of substances present in the Durance River, 22+. Finally, point source pollution (industry) and diffuse source pollution (agriculture), which both have not been part of this case study, should not be disregarded.

4.9. Discussion of the Results

Structured along the answers to question 1 to 4, this chapter sums up the main results, points out strengths and weaknesses, and stresses crucial aspects arising from this thesis.

4.9.1. Question 1: The Development of the DPSIR-CC Model and its Application

Prior modifications of the DPSIR model and various approaches towards integrating climate change into RBM have provided the basis for the creation of the DPSIR-CC model. Subsequently the DPSIR-CC model has been put to test by applying it to the case of water management in the Durance catchment. A semi-quantitative evaluation of the impacts produced by anthropogenic activities and by climate change provided the structure for analysing cause and effect of changes in natural conditions. The assessment of potential consequences for anthropogenic activities and the impact assessment for the water quality status have hence yielded clear results, subsequently subject to discussion.

The simple structure of the model itself is certainly a strength, which allows placing side by side an analysis of climate change impacts on human activities (drivers) and on components determining the natural condition of the water body (state), which ultimately create implications for “environmental and socio-economic interests” (Mateus and Campuzano 2008).

Simplifications applied to facilitate the first application of the model have clearly been a weakness. Therefore, the following discussion highlights those aspects, which should be further elaborated in order to improve the functioning of the DPSIR-CC model.

Attributing the sign “+” has been reduced to those effects which put additional constrain on water bodies without differentiating the magnitude of each impact. However, the case study points out that some impacts could, overall, produce stronger implications than others. If the amount of runoff strongly depends on water stored as snow or ice in mountainous areas, trends of increasing temperatures could already affect the headwaters. The example of the Durance River, originating in the Alps and flowing through Mediterranean climate, shows that attributing only one “+” to direct climate change effects on hydrology does not reflect the strong decrease projected for the snow storage capacity of the Alps, namely -25% (see Chapter 4.2.3.). Furthermore, considering that “the magnitude of the change in mean annual discharges [resulting from Climate Change] is higher than the intensity of the change in water abstraction" (Andrew and Sauquet 2017, 11) in the Durance catchment, the attribution of "+" clearly needs to be refined.

The use of inconsistent terminology in the DPSIR model when it comes to assessing the relation drivers-pressures and state-impact has been discussed in literature (see: Elliott et al. 2017, 28; Oesterwind et al. 2016, 11).While the link between climate change-drivers-pressures did not pose difficulties, this thesis reveals that the definition of "impact" needs further clarification. The first part of the case study analysed how the environment reacts to changes triggered directly by anthropogenic activities and by climate change. However, the consequences on hydropower production have not been assessed as an "impact" per se, whereas potential implications for ecological and chemical water status were considered as "impact". This imprecise use of the component "impact" should be subject to further research in order to make the DPSIR-CC suitable for analysing socio-economic "impacts" as a result of changes in the "state" of the water body. This reiterates what Cooper (2013) and Elliott et al. stressed as being the result of unclear terminology used in the DPSIR model, namely the "confusion between the impacts on the environment i.e. changes in State, and the impacts on human Welfare" (Elliott et al. 2017, 29).

Furthermore, the DPSIR-CC accounts solely for aspects exacerbating the water quality status, whereas certain anthropogenic activities or climate change related alterations of the hydrologic cycle might produce positive implications for the ecological and chemical status of surface water bodies. For example, a study conducted in the Durance catchment has shown that the artificial gravity-fed channels could serve as "biodiversity-management tools [...]" in providing "an efficient preventive measure to address the anticipated effects of warming in Mediterranean regions" (Aspe et al. 2014, 1976). Additionally, Guivier states that the highly regulated flow regime downstream the reservoir could partially offset the rapid changes and strong fluctuations in flow potentially occurring with projected global warming trends in the Durance River (2018,13).

4.9.2. Question 2: The Effects of Climate Change on Drivers-Pressures-State

The answer to question 2 shows that hydrology is the most vulnerable state element, strongly influenced by direct effects of global warming as well as by anthropogenic pressures, 15+. The case study clearly demonstrates the additive effects, a result of anthropogenic drivers being influenced by climate change and direct impacts of climate change on natural conditions of surface water bodies.

Terminological difficulties with regards to the relationship state-impact have been subject to the discussion with regards to question 1.

4.9.3. Question 3: Consequences for Anthropogenic Water Use

The answer to question 3 shows that anthropogenic activities in the Durance catchment could be strongly affected by climate change. Hydropower production at the Serre-Ponçon reservoir could face challenges emerging from the reduced amount of water and temporal shifts or runoff in the Durance River. Potential implications for hydropower production arising from conflicting water use were not subject to the case study, nevertheless they could create significant constraints for the operation of hydropower installations. Hence, agriculture, abstracting the largest amounts of water and highly climate-sensitive, could produce negative consequences for hydropower production. Andrew and Sauquet project that “the volume of 200 million m^3 stored in the Serre-Ponçon reservoir for agriculture is not sufficient to meet the total irrigation needs every year by the 2050” (2017, 11), assuming human water use practices do not change. Considering that the peak in water demand for agricultural irrigation as well as for tourism and leisure occur at the same time as water resources get more and more scarce, depleting the storage capacity for increasing demand in summer could severely affect operation of hydropower installations in winter.

Therefore, Andrew and Sauquet conclude that water management should “minimize seasonal variations in storage in order to limit the risk of water shortage “(ibid) and deal with conflicting interests potentially arising from multiple anthropogenic activities. This highlights the need to develop robust responses based on long-term climate projections while considering that climate change affects anthropogenic drivers as well as directly impacting the aquatic environment water.

4.9.4. Question 4: Impact Assessment on Water Quality Status

Based on the analysis in the previous chapter, the answer to this question describes potential impacts of direct effects from climate change and anthropogenic pressures exerted on the Durance River.

The complexity produced by the fact that multiple aspects are relevant to determining the water quality status has constrained the case study to analysing a limited number of state components. In addition to describing potential impacts on BQE, the case study highlights the need to consider that changes in hydrology, 15+ and temperature, 7+, conditions could strongly influence the chemical status of the river, 22+.

The results demonstrate that temperature, an important determinant for the biological quality elements and chemical water status, could be subject to additive effects, caused on the one hand from existing anthropogenic pressures and on the other hand resulting from global warming, 7+.

Furthermore, the fact that hydro-morphological state is presently at moderate status points out that long-term climate projections could similarly impact restoration measures. When it comes to analysing potential changes in water quality, literature research on climate change impacts in freshwater systems has shown that the understanding of the linkage between hydrology and biological indicators needs to be strengthened. Due to limited resources about climate change impacts in the ecological quality of rivers, studies on lakes have complemented the existing sources. This leads to the conclusion that further research is needed to build a thorough understanding of how multiple pressures could impact rivers thereby potentially causing the failure to achieve the WFD’s goals.

To conclude, despite the case study was simplified and limited to analysing few aspects in water management, its application in the case study has proven that the DPSIR-CC model generates clear results. First, changes in hydrology are projected to strongly constrain the operation of hydropower installations in the Durance catchment. Second, good ecological potential might not be reached as a result of three processes. This could occur either due to biological quality elements deteriorating strongly, or as a result of restoration measures being impeded by projected changes in hydrology, or from severe impacts on substance concentration causing the chemical status to degrade.

5. Conclusion

By integrating climate change into the DPSIR model, this thesis illustrates how the modification of existing tools in RBM could serve to tackle emerging challenges. The application of the DPSIR-CC model highlights, in essence, two aspects. First, by the example of hydropower production in the Durance catchment, the testing of the framework shows how direct effects of climate change on drivers and the state of the water body could influence anthropogenic water use. Second, the case study illustrates that the impact on the ecological and chemical status of surface water bodies, resulting from anthropogenic water use and direct effects of climate change, is more than the sum of human pressures exerted on the aquatic environment.

By considering long-term climate projections as integral part of RBM, this thesis stresses the need to establish sustainable water management policies on an EU-level, to ensure that the conservation and preservation of good ecological and chemical status is pursued, also post 2027. Although, not all water bodies in the EU might have reached the ambitious goals of the WFD, water management needs to develop a systematic approach towards dealing with the imminent consequences and future signs of climate change induced alterations of the environment. This thesis has shown that the DPSIR-CC model could be a first step towards integrating climate change into all aspects of RMB. By assessing the links between human activities, climate change and natural water conditions with the DPSIR-CC model, it reveals that long-term climate projections and complex interactions of multiple stressors on water bodies should be subject to further research. Finally, this thesis stresses the need to strengthen the science-policy-interface in EU-RBM in order to tackle unprecedented challenges in water management.

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