Large scale adaptation strategies to climate change in the water-sector: An overview of the water allocation model WatCAM

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Abstract

For this study, the Water and Climate Adaptation Model (WatCAM) was investigated and improved. WatCAM is a water allocation model developed by FutureWater. It is based on other water allocation models like WEAP, but is more simplified. As a result, WatCAM requires little effort to set up and can be run with very low computation times. The ability to study impacts of adaptation strategies makes WatCAM a valuable tool. WatCAM was applied to a single river basin (water province) in order to gain better understanding about the model. In this case study, the effects of different future predictions (RCP and SSP scenarios) are investigated. It became evident that the already present water gap is only expected to increase in the future, independent of the scenario combination. An analysis of the adaptation strategies showed that – even with all pre-defined adaptation strategies – it is impossible to close the water gap in this water province. A comparison of WatCAMs global results with other studies indicate that results from WatCAM compare very good with those studies, but there is definitely room for improvement. This comparison led to a change in the groundwater component of WatCAM, making both the groundwater recharge and maximum extraction values more realistic. Furthermore, it is no longer possible for the model to completely deplete the groundwater reservoirs, which led to improbable situations. The final global results show that there are already plenty of water provinces extracting groundwater in an unsustainable way, and most of these areas are currently already experiencing water shortage. WatCAM simulated that these problems are expected to get worse in the future. Overall, WatCAM is a great tool providing the possibility to quickly analyze the current and future situation, and to assess the impacts of adaptation strategies.

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1 Introduction

In this chapter, the introduction for the study is described. It is divided in three sections: a section describing the motivation behind this study, a section containing the research objectives, and a section describing the outline of this report.

1.1 Motivation

Water availability is a key concern already today in many areas in the world, but even more for the future (Immerzeel, van Beek, & Bierkens, 2010; Schewe et al., 2014). Climate change together with population growth will likely put more stress on the water resources (Arnell, 2004; Vorosmarty, 2000). This does not only have consequences for humanity, but also on the environment (Hamdy, Ragab, & Scarascia-Mugnozza, 2003; Rijsberman, 2006). In some areas, a gap between the water demand and supply is already present, and is expected to increase with the future (Sowers, Vengosh, & Weinthal, 2011). To adapt to this future situation and reduce the water gap it is important to assess the impacts of different possible future scenarios.

There are multiple adaptation strategies available; increasing the capacity of reservoirs and/or increase water reuse are just a few examples. However, these adaptation strategies are related to certain costs. For decision makers, it is important to choose the right strategy: reducing the water gap in the most cost-effective way.

Currently, there are multiple tools available, able to deal with water demand and supply problems (WEAP, MODSIM). However, these models require some time to set up, and do not contain a cost/benefit functionality. Furthermore, these models are difficult to run in batch mode, and on a global scale. As a result, FutureWater created the Water and Climate Adaptation Model (WatCAM). This model enables the user to quickly analyze the water availability across the global, and perform some adaptation scenario runs.

1.2 Objectives

This study has multiple objectives regarding the WatCAM model. The first objective is to analyze and improve the current WatCAM model. This includes both the model structure itself as well as the used input data. The important data and parameters will be investigated by applying WatCAM to an area with sufficient observations. For this case study, the adaptation strategies are inspected as well. Next, the performance of WatCAM over the entire globe is studied, both for the current situation and the future.

In order to reach those objectives, the following research question used in this study: *What are the strong and weak points of WatCAM, and how does it function on a global scale?* This research question is divided into several sub-questions:

- How does WatCAM work?
- What is the performance of WatCAM, when applied to a single area?
- How do the adaptation strategies translate into less water stress?
- How does WatCAM perform on a global scale?

1.3 Report outline

This report is divided into several chapters. Firstly, a model description of WatCAM is given, including all included concepts and equations. Next, the results from applying WatCAM to a case study (the Segura basin) are presented. This chapter is followed by the results from a global run of WatCAM, including a comparison with several other similar studies. This and the previous chapter contain both the results and a discussion of the results. Subsequently, the chapter with conclusions can be found, where an answer is given to the research question described earlier. Lastly, the recommendations for improving WatCAM and/or other interesting studies are presented.

2 WatCAM

For this study, the Water and Climate Adaptation Model (WatCAM) was used. WatCAM is a water allocation model: distributing the available water between different users. A model description, the input and used formulas can be found in this chapter.

A version of WatCAM was already present (used by Brandsma et al. (2015)), and was originally written in Excel with a wrapper in Python for iterative runs and scenarios. For this study, the WatCAM model was translated entirely into Python code, in order to have a more transparant and computaionally efficient model. Changes were made to the model during this tranformation: several small errors and inconsistencies were fixed, but some larger changes were made as well. The description in this chapter is based on the new version of WatCAM.

2.1 Model description

As described earlier, WatCAM is a water allocation model. It calculates the available water and distributes this water between the different water demanding sectors. Each water demand sector can be given a certain priority within the water allocation process, making sure that meeting the projected demand of this sector gains more weight during the allocation process. Water can be extracted from streams (surface water), reservoirs and groundwater: in that particulair order. WatCAM is able to give a quick overview of the water availability, demands and unmet demand for any area around the globe. The user is able to investigate the cost-benefit ratio based on different adaptation measures, which try to close the gap between supply and demand (Brandsma et al., 2015).

WatCAM operates on a monthly time step, and distributes water based on water provinces (WP). Water provinces are similar to river basins, but are divided based on administrative borders (e.g. country or province borders). These water provinces enables to model to make use of socio-economic changes, which are based on changes within countries and/or provinces.

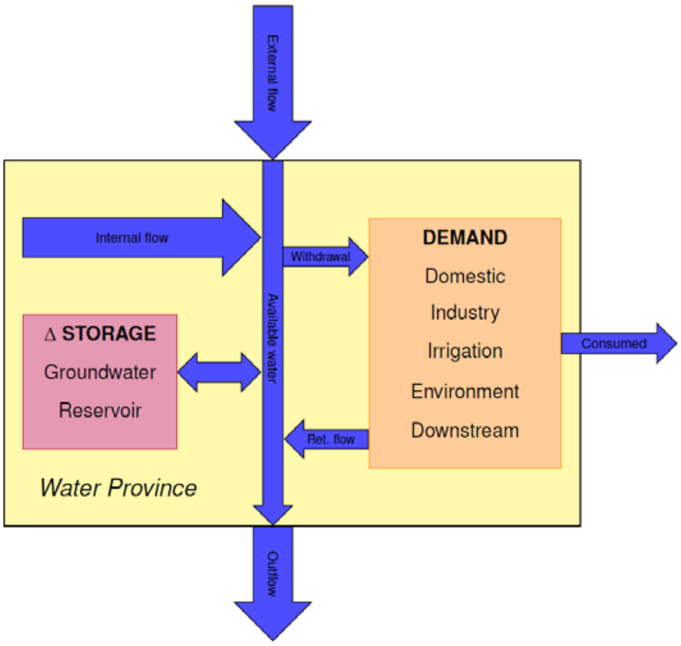

Figure 2.1: Schematic overview of WatCAM. The yellow box represents a water province.

Climate change is an important factor when determining the amount available water within each time step. The user can choose between four different climate change scenarios, and between five different socio-economic changes. The input data used by WatCAM will change according to the scenario combination. In order to determine the amount of available water (depending on the climate change scenario), output from a global hydrological model is used: the PCR-GLOBWB model. This hydrological model has been ran for each climate change scenario, and the output has been transformed so that WatCAM can use this data correctly for each water province. For the socio-economic changes, input data about population, domestic and industrial demand is prepared, and WatCAM reads the corresponding files based on the chosen scenario combination. A more detailed description is given by Brandsma et al. (2015).

2.2 Input variables

As described above, WatCAM requires several input variables, most of which are dependent on the scenario combination. Before running the model, a set of parameters and input variables need to be defined. Based on these values, WatCAM can start simulating the water provinces. All variables – parameters, internal and output variables – are presented in Table 2.1. The internal variables are needed in order to perform all the equation, but are not necessarily interesting to the end user. If the end-user is interested in these values, the code can easily be changed. The parameter values are partially chosen by the user; some are dependent on the water province (e.g. the area).

In this table, the input variables are not presented. These are dependent on the chosen scenario combination. Below, an overview of all input files and their relative location to the model is presented:

- ...\WatCAM\Input\General_FUT\

Res_cap.tss.npy	Reservoir capacity
gw_cap.tss.npy	Groundwater capacity
Hist_Flo_m3.tss.npy	Historical/pristine flow
irr_area_m2.tss.npy	Irrigated area
ExtFlowBAU.tss.npy	External flow for business as usual, if run of 1 WP

- ...\WatCAM\Input\SSPx\

population.tss.npy	Population
dom_l_p_day.tss.npy	Domestic water demand (liter per capita per day)
demIndustry_m3.tss.npy	Industrial demand

- ...\WatCAM\Input\RCP_x.x\

Etref_mm.tss.npy	Reference evapotranspiration
IntFlow.tss.npy	Internal generated flow
ExtFlow.tss.npy	External generated flow[1]

- ...\WatCAM\WatProv\

WatProv_xx.csv	Selects which WPs should be ran

Please note that not all variables are depending on the chosen scenario combination (e.g. the reservoir and groundwater capacities). It is assumed that these variables have a fixed time series, independent of the scenario combinations. The user still can control these values by choosing different parameter values.

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[1] This file is continuously updated during the run. If a single WP is run, the business as usual scenario is used to determine the external flow.

Domestic demand

Domestic water demand is a function of the population and the Gross Domestic Product (GDP). First a relation is identified between per capita domestic water withdrawal and the GDP per capita (see Figure 2.2). The rationale behind this is that with an increasing GDP per capita, the domestic water withdrawals per capita will also increase (washing machines, bathrooms, watering gardens, swimming pools, etc.). The increase in water withdrawals is not linear but the growth rate reduces with increasing GDPP. Once the GDP reaches 70.000 US$ per capita, it is assumed that the per capita water requirement remains constant (Brandsma et al., 2015).

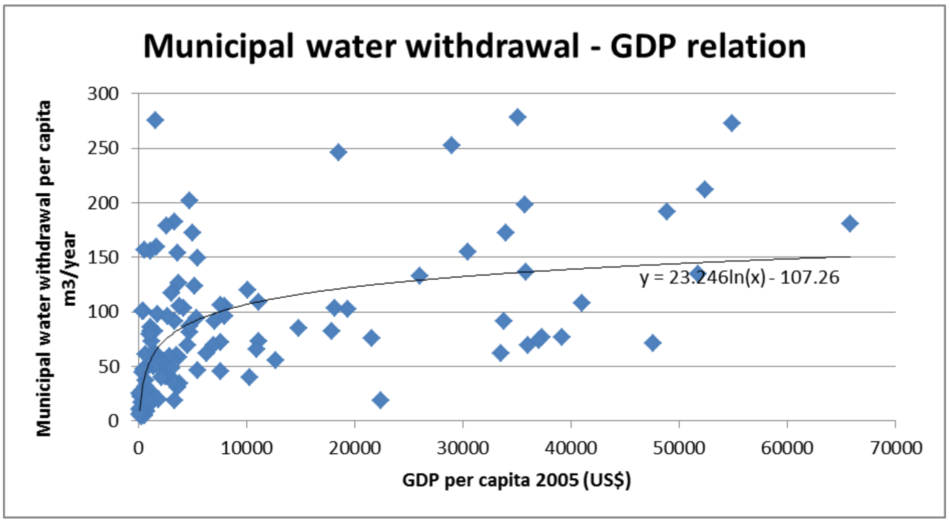


Figure 2.2: Relation between domestic water withdrawal and GDPP (Brandsma et al., 2015)

This resulted in the following equation:

$$DWW_{year} = 23.246 \cdot \ln(GDPP_{year}) - 107.26 \tag{2.1}$$

where DWW_{year} equals the domestic water demand in m^3 year^{-1} capita^{-1}, and $GDPP_{year}$ the gross domestic product per capita in US$ for the corresponding year. Using this equation, one can determine the water demand per capita, given a certain GDP_{year}. By multiplying the value with the population, one can determine the projected domestic water demand.

Industry demand

The industrial water demand is calculated as follows:

$$IWW_{year} = IWW_{year-1} \cdot \frac{GDP_{year}}{GDP_{year-1}} \cdot \frac{GDPP_{year-1}}{GDPP_{year}} \tag{2.2}$$

where IWW is the industrial water withdrawal in m^3 year^{-1}, GDP the gross domestic product, $GDPP$ the gross domestic product per capita, for the corresponding and previous year. If a country produces more GDP, but does not get richer per person (constant GDPP), industrial water demand will change equally to the GDP increase. If the country also gets richer per person, it is more inclined to safe water.

RCP time series

The reference evapotranspiration and internal flow are both outputs from the PCR-GLOBWB model. This model has been ran for each scenario, and both the reference ET and the internal flow were saved for each water province. The external generated flow is not an output of PCR-GLOBWB, but is updated dynamically during the WatCAM model run. Here, outflows of each water province are written to this file, so that the downstream water province can use this water as external generated flow.

Table 2.1: Overview of all variables present in WatCAM. Variables are separated in three groups: parameters, internal and output variables.

PARAMETERS			**INTERNAL**			**OUTPUT**		
Name	**Description**	**Unit**	**Name**	**Description**	**Unit**	**Name**	**Description**	**Unit**
Calibration	Calibration factor	frac	IND_demand	Industry demand scenario	m^3 mo^{-1}	MM	Month	
DESAL	Water desalinated	10^6 m^3	DOM_demand	Demand domestic scenario	L C^{-1} day^{-1}	FLO_internal	Internal flow	m^3 mo^{-1}
DOM_CONS_F	Domestic consumed fraction	frac	IRR_area	Irrigated area scenario	m^2	FLO_external	External flow	m^3 mo^{-1}
DOM_REU	Domestic reuse	frac	ENV_demand	Environmental demand scenario	m^3 mo^{-1}	FLO_total	Total generated flow	m^3 mo^{-1}
DOM_RPI	Domestic priority	1-99	DWN_demand	Downstream demand scenario	m^3 mo^{-1}	FLO_ava	Available surface water	m^3 mo^{-1}
DWN_DEM	Downstream demand (frac of historical)	frac	INFORMAL_sup	Informal supply	m^3 mo^{-1}	TOTAL_ava	Total available water	m^3 mo^{-1}
DWN_PRI	Downstream priority	1-99	RES_ava	Potential available reservoir water	m^3 mo^{-1}	RES_inflow	Reservoir inflow	m^3 mo^{-1}
ENV_FRAC	Fraction of flow as env demand	frac	GWT_ava	Potential available groundwater	m^3 mo^{-1}	GWT_inflow	Groundwater inflow	m^3 mo^{-1}
ENV_PRI	Environment priority	1-99	RES_storage_new	Updated reservoir storage	m^3	FLO_extracted	Water extracted from surface water	m^3 mo^{-1}
ENV_USE	Environmental use	frac	GWT_storage_new	Updated groundwater storage	m^3	RES_extracted	Water extracted from reservoir	m^3 mo^{-1}
Ext_User	External flow user given (frac of pristine)	frac	REQ_withdrawal_DOM	Required withdrawal domestic	m^3 mo^{-1}	GWT_extracted	Water extracted from groundwater	m^3 mo^{-1}
GWT_INIT	Initial Groundwater storage	frac	REQ_withdrawal_IND	Required withdrawal industry	m^3 mo^{-1}	FLO_out	Water going out of the waterprovince	m^3 mo^{-1}
GWT_MAX	Groundwater maximum extraction	frac	REQ_withdrawal_IRR	Required withdrawal irrigation	m^3 mo^{-1}	RES_storage	Reservoir storage	m^3
GWT_RECH	Groundwater recharge	frac	REQ_withdrawal_ENV	Required withdrawal environment	m^3 mo^{-1}	GWT_storage	Groundwater storage	m^3
IND_DEM	Industry demand fraction	frac	REQ_withdrawal_DWN	Required withdrawal downstream	m^3 mo^{-1}	GROSS_dem_DOM	Domestic gross demand	m^3 mo^{-1}
IND_CONS_F	Industry consumed fraction	frac	REQ_withdrawal_tot	Total required withdrawal	m^3 mo^{-1}	GROSS_dem_IND	Industry gross demand	m^3 mo^{-1}
IND_PRI	Industry priority	1-99	ACTUAL_withdrawal_DOM	Actual withdrawal domestic	m^3 mo^{-1}	GROSS_dem_IRR	Irrigation gross demand	m^3 mo^{-1}
IND_REU	Industry reuse	frac	ACTUAL_withdrawal_IND	Actual withdrawal industry	m^3 mo^{-1}	GROSS_dem_ENV	Environment gross demand	m^3 mo^{-1}
INFORMAL	Informal extraction fraction	frac	ACTUAL_withdrawal_IRR	Actual withdrawal irrigation	m^3 mo^{-1}	GROSS_dem_DWN	Downstream gross demand	m^3 mo^{-1}
IRR_AREA	Irrigation demand fraction	frac	ACTUAL_withdrawal_ENV	Actual withdrawal environment	m^3 mo^{-1}	GROSS_dem_tot	Total gross demand	m^3 mo^{-1}
IRR_COR	Irrigated land use factor	frac	ACTUAL_withdrawal_DWN	Actual withdrawal downstream	m^3 mo^{-1}	DELIVERD_water_DOM	Delivered water domestic	m^3 mo^{-1}
IRR_CONS_F	Irrigation consumed fraction	frac	ACTUAL_withdrawal_tot	Total actual withdrawal	m^3 mo^{-1}	DELIVERD_water_IND	Delivered water industry	m^3 mo^{-1}
IRR_PRI	Irrigation priority	1-99	RETURN_DOM	Return flow domestic	m^3 mo^{-1}	DELIVERD_water_IRR	Delivered water irrigation	m^3 mo^{-1}
IRR_REU	Irrigation reuse	frac	RETURN_IND	Return flow industry	m^3 mo^{-1}	DELIVERD_water_ENV	Delivered water environment	m^3 mo^{-1}
RES_extra	Additional reservoir created	10^6 m^3	RETURN_IRR	Return flow irrigation	m^3 mo^{-1}	DELIVERD_water_DWN	Delivered water downstream	m^3 mo^{-1}
RES_INIT	Initial reservoir storage	frac	RETURN_ENV	Return flow environment	m^3 mo^{-1}	DELIVERD_water_tot	Total delivered water	m^3 mo^{-1}
RES_MAX	Reservoir maximum extraction	frac	RETURN_ENV	Return flow downstream	m^3 mo^{-1}	CONSUMED_DOM	Domestic consumed	m^3 mo^{-1}
URB_DEM	Urban demand fraction	frac	RETURN_tot	Total return flow	m^3 mo^{-1}	CONSUMED_IND	Industry consumed	m^3 mo^{-1}
WatProvID	Water province ID	int				CONSUMED_IRR	Irrigation consumed	m^3 mo^{-1}
						CONSUMED_ENV	Environment consumed	m^3 mo^{-1}
						CONSUMED_DWN	Downstream consumed	m^3 mo^{-1}
						CONSUMED_tot	Total consumed	m^3 mo^{-1}
						UNMET_DOM	Unmet domestic	m^3 mo^{-1}
						UNMET_IND	Unmet industry	m^3 mo^{-1}
						UNMET_IRR	Unmet irrigation	m^3 mo^{-1}
						UNMET_ENV	Unmet environment	m^3 mo^{-1}
						UNMET_DWN	Unmet downstream	m^3 mo^{-1}
						UNMET_total	Total unmet	m^3 mo^{-1}
						BAL	Water balance	m^3

2.3 Demand supply concept

In WatCAM, the user can define a certain consumed and reuse fraction for each demand sector, with the exception of environment (only haves a consumed fraction) and downstream demand. In order to calculate the required withdrawal from the water supply, the concept presented in Figure 2.4 is used.

The idea behind this concept, is that the projected demand is the know variable for each demand sector (see above). This projected demand is the sum of withdrawn water from the water supply, and water that is reused from the non-consumed fraction. In order to correctly distribute water within WatCAM, it is important to know the required withdrawal from the water supply. Since the used defined a consumed fraction and a reuse fraction, it is possible to calculate this flux.

In WatCAM, the main interest is calculating the unmet demands for the different demand sites. This unmet demand needs to be calculated based on the projected demand. Since one cannot assume that the available water always meets the required withdrawal, a second calculation step is needed, in order to determine the (actual) amount of water delivered. In the second calculation step, the amount actual withdrawn is known, together with the consumed fraction and reuse fraction. Based on these three values, the water delivered can be calculated, together with the amount of consumed water and the return flow. This return flow is added to the outflow of the water province. Using the projected and actual demand (water delivered) one can calculate the unmet demand.

The equations used to determine all these fluxes can be found in Section 2.5, and some examples can be found in Appendix A.2 .

2.4 Scenarios

Multiple scenarios are used to predict the future. In this study, a distinction is made between climate change and socio-economic change scenarios. The scenarios are briefly described in this section.

2.4.1 Climate changes

The four climate change scenarios used for this study are all based on the scenarios presented by the IPCC. These four scenarios range from a declining change in radiative forcing to a rising change in radiative forcing. These scenarios are summarized in Table 2.2. More details are described by Brandsma et al. (2015).

Table 2.2: Representative climate change projections for 2100 (Moss et al., 2010).

	Radiative forcing (W/m^2)	CO_2 equivalent forcing (ppm)	Rate of change in radiative forcing
RCP 8.5	8.5	1350	Rising
RCP 6.0	6.0	850	Stabilizing
RCP 4.5	4.5	650	Stabilizing
RCP 2.6	2.6	450	Declining

2.4.2 Socio-economic changes

Five different scenarios are used for this study. These scenarios are based on different population and economic growth expectations, again based on the IPCC scenarios. These scenarios can be best summarized in Figure 2.3. For more details, see Brandsma et al. (2015).

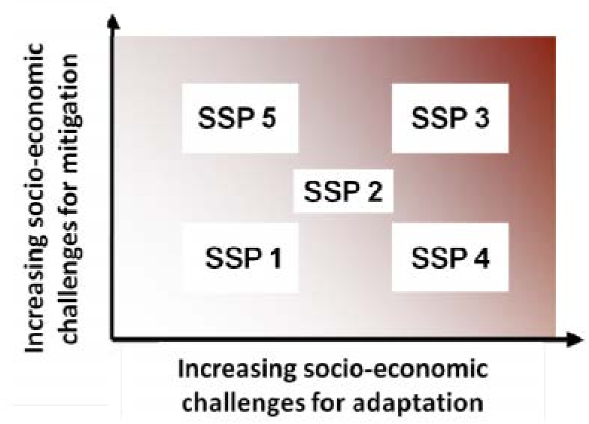


Figure 2.3: The scenario space to be spanned by SSPs according to the IPCC (Edenhofer et al., 2010).

2.5 Equations

In this section, the equations of the model are presented and explained.

Before the model starts to calculate the water supply and demand values for each month, some initial calculations need to be performed. The reservoir capacity and initial reservoir and groundwater storages are calculated using the following equations:

$$RES\_capacity = RES\_capacity\_org + RES\_extra \cdot 1000000 \tag{2.3}$$

$$RES\_storage = RES\_capacity \cdot RES\_INIT \tag{2.4}$$

$$GWT\_storage = GWT\_capacity \cdot GWT\_INIT \tag{2.5}$$

where RES_extra is a parameter, determining how much additional reservoir capacity is created in 10^6 m^3. RES_INIT and GWT_INIT are both parameters, representing the fraction of the capacity that is initially filled.

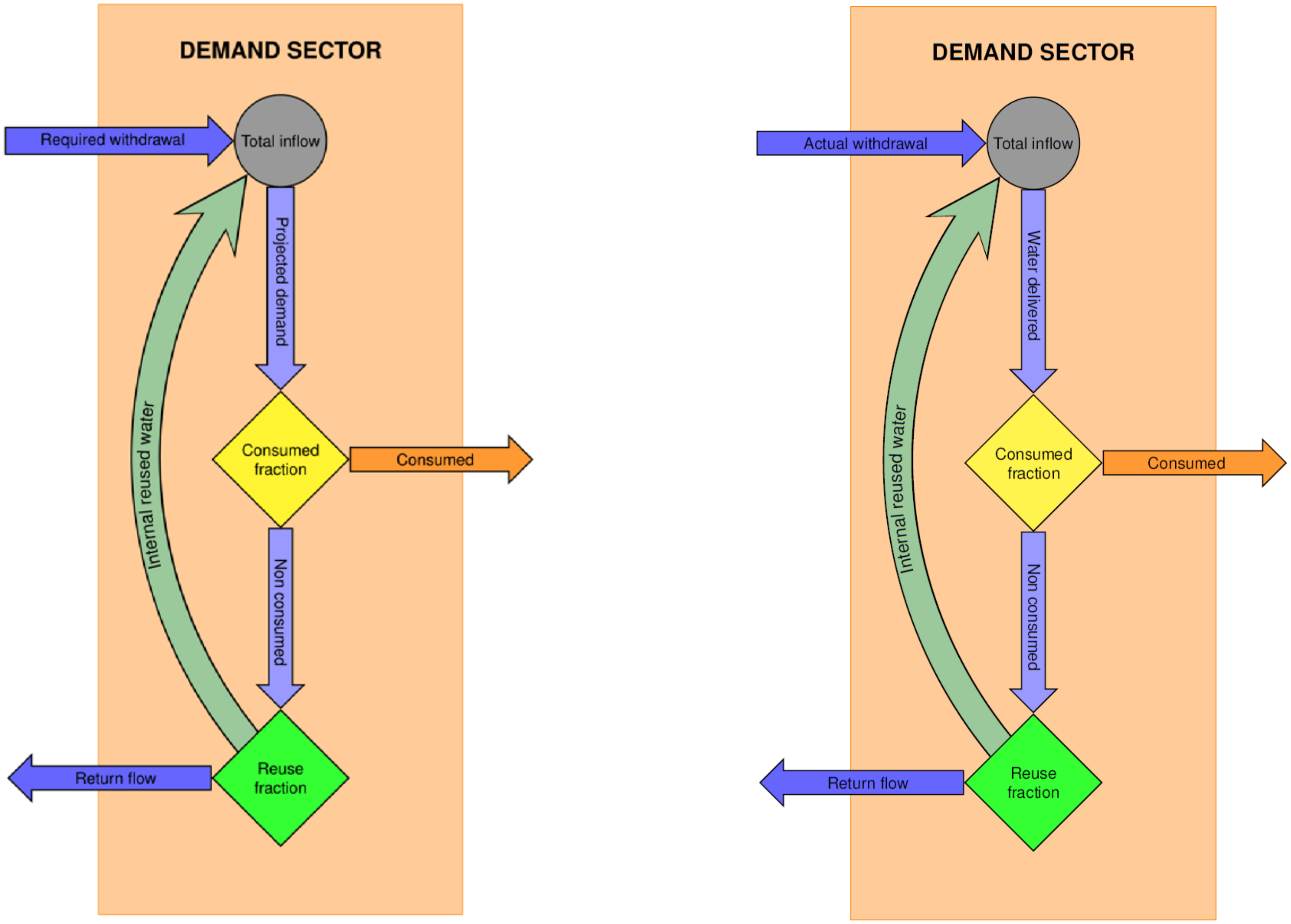
Next, the internal, external and total flow are calculated:

$$FLO\_internal = FLO\_internal\_org \cdot Calibration \tag{2.6}$$

$$FLO\_external = \begin{cases} FLO\_external\_org, & Ext\_User = 0 \\ FLO\_pristine \cdot Ext\_User, & Ext\_User > 0 \end{cases} \tag{2.7}$$

$$FLO\_total = FLO\_internal + FLO\_external + \frac{DESAL}{12} \cdot 1000000 \tag{2.8}$$

where $Calibration$ is a parameter able to compensate for any possible over- or underestimations made by the PCR-GLOBWB model. The user can define the Ext_User parameter, making it able to define the external flow as a fraction of the pristine flow. If this parameter is equal to zero, the original external flow is used (fraction of outflow of upstream water province). The total flow is the sum of the internal and external flow, and the amount of water that is desalinated. This amount is determined by the $DESAL$ parameter, which is presented in 10^6 m^3 $year^{-1}$.



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(a) Step1: Calculating the required withdrawal, given the gross demand, consumed fraction and reuse fraction

(b) Step 2: Calculating the water delivered, given the actual withdrawal, consumed fraction and reuse fraction

Figure 2.4: Demand and supply concept, as present in WatCAM. Calculations occur in two steps, in order to correctly calculate the unmet demands; please note the differences in terms in each step.

Next, the amount of available water is calculated, according to the following formulas:

$$GWT\_inflow = min(FLO\_internal \cdot GWT\_RECH, \\ GWT\_capacity - GWT\_storage) \quad (2.9)$$

$$INFORMAL\_sup = (FLO\_internal - GWT\_inflow) \cdot INFORMAL \quad (2.10)$$

$$RES\_ava = RES\_storage \cdot RES\_MAX \quad (2.11)$$

$$GWT\_ava = GWT\_storage \cdot GWT\_MAX \quad (2.12)$$

$$FLO\_ava = FLO\_total - GWT\_inflow - INFORMAL\_sup \quad (2.13)$$

$$TOTAL\_ava = FLO\_ava + RES\_ava + GWT\_ava \quad (2.14)$$

where the amount of water flowing into the groundwater is calculated first, based on a fraction (GWT_RECH) of the internal flow; but this flow is limited by the unsaturated part of the groundwater reservoir. The illegally extracted surface water is calculated using the $INFORMAL$ parameter. Both the potential reservoir and groundwater outflow are based on a fraction of the current storage. This water is only used in case when the available surface water (FLO_ava) is insufficient. The total available water ($TOTAL\_ava$) is the sum of the available surface water, reservoir and groundwater outflow.

With knowledge about the amount of available water, is becomes possible to distribute water between the different demand sites. In order to know how much water each demand site requires, the demand values determined in Section 2.2 are corrected using the following equations:

$$DOM\_demand = DOM\_demand\_org \cdot URB\_DEM \quad (2.15)$$

$$IND\_demand = IND\_demand\_org \cdot IND\_DEM \quad (2.16)$$

$$IRR\_area = IRR\_area\_org \cdot IRR\_AREA \quad (2.17)$$

$$ENV\_demand = min(FLO\_pristine \cdot ENV\_FRAC, 0.1 \cdot AREA\_WP) \quad (2.18)$$

$$DWN\_demand = \begin{cases} DWN\_demand\_org, & DWN\_DEM = 0 \\ FLO\_pristine \cdot DWN\_DEM, & DWN\_DEM > 0 \end{cases} \quad (2.19)$$

where each demand value is multiplied with a certain fraction. These fractions make it possible for the end user to quickly reduce or increase the demand of each sector by a fraction. The same is done with the irrigated area. The environmental demand is limited by the volume of water corresponding to 100 mm over the entire water province. This correction is implemented in order to counteract very high environmental demand values (which were present in some water provinces). As for the downstream demand, the user can chose to either use a fraction of the pristine flow, or to use the default implemented downstream demand values (which equals zero in the current model version).

However, the units of for each demand type are not yet correct, so the following equations are used to calculate the monthly projected demand for each demand site to m^3 $month^{-1}$:

$$GROSS\_dem_{DOM} = Population \cdot \frac{DOM\_demand}{1000} \cdot 30.5 \quad (2.20)$$

$$GROSS\_dem_{IND} = IND\_demand \quad (2.21)$$

$$GROSS\_dem_{IRR} = IRR\_area \cdot \frac{ET\_ref}{1000} \cdot \frac{1}{IRR\_COR} \quad (2.22)$$

$$GROSS\_dem_{ENV} = min(ENV\_demand, 0.2 \cdot FLO\_total) \quad (2.23)$$

$$GROSS\_dem_{DWN} = DWN\_demand \quad (2.24)$$

where it can be visible that DOM_demand is given in L day^{-1} $captita^{-1}$. Furthermore, the irrigation demand is calculated based on the irrigated area and the reference evaporation. This demand is multiplied with a correction factor, which reflects the use of the irrigated land (type of crop and usage throughout the year), and the climate of the water province. This factor is calculated as follows: $IRR\_COR = min(\frac{ET\_ref}{ET\_ref - FLO\_internal}, 2)$. The correction factor will be equal to 1 when the internal flow is very low, and will be 2 when the internal flow is very high. Here the limit of 2 chosen arbitrarily in order to prevent very high correction factors. Finally, the environmental demand is again limited, this time by 20% of the total flow (arbitrarily chosen).

Based on the projected demand values, the required extraction from the water supply can be calculated as follows, keeping the concept of Figure 2.4 in mind:

$$POT\_consumed_{sect} = GROSS\_dem_{sect} \cdot CONS\_F_{sect} \tag{2.25}$$

$$POT\_reuse_{sect} = (GROSS\_dem_{sect} - POT\_consumed_{sect}) \cdot REU_{sect} \tag{2.26}$$

$$REQ\_withdrawal_{sect} = GROSS\_dem_{sect} - POT\_reuse_{sect} \tag{2.27}$$

where $sect$ is replaced for the corresponding demand type. Please note that the downstream demand sector cannot reuse or consume water, so the required withdrawal is equal to the gross demand. For the environmental demand, the consumed fraction is applied at the end of the allocation process. These equations result in a required withdrawal for each sector, which can be used to distribute the water between the different demand sectors based on their priorities.

The user can define different priorities to each demand site, ranging between 1 and 99. A value of 1 corresponds to the highest priority, and 99 to the lowest priority. WatCAM will try to distribute water based on the ratios between the different demand sites. The water is simultaneously distributed between the different demand sites, instead of the step wise approach (from highest to lowest priority) used by e.g. WEAP (see Appendix A.1 for some examples). In order to correctly distribute the water, a set of equations are solved within a loop. These equations are presented below, where $sect$ means that the same equation is performed for each demand site (DOM, IND, IRR, ENV, DWM):

$$PRI\_TOT = \frac{TOTAL_{ava}}{\frac{REQ\_withdrawal_{sect}}{PRI_{sect}} + \cdots} \tag{2.28}$$

where PRI_TOT can be understood as a correction factor only used when the total demanding flow is higher than the total available outflow. When the total demanding flow is higher than the total available water, this factor will be lower than every priority. This becomes relevant in the next equation:

$$\begin{gathered} ADJ = min([PRI_{sect}, \ldots, PRI\_TOT]) \\ for\ [REQ\_withdrawal_{sect}, \ldots, TOTAL\_ava] > 0 \end{gathered} \tag{2.29}$$

where ADJ contains the highest priority (lowest value). Only the priorities of demand sites with a demand that is not yet satisfied (demand > 0) are taken into account.

Next, the actual withdrawn water can be calculated, using the following equation:

$$supply_{sect} = ADJ \cdot \frac{REQ\_withdrawal_{sect}}{PRI_{sect}} \tag{2.30}$$

where – assuming that there is enough water available – the $supply_{sect}$ term will be equal to $REQ\_withdrawal_{sect}$ for the demand site with the highest priority, since $ADJ == PRI_{sect}$. For demand sites where $ADJ\ != PRI_{sect}$, only a fraction of the required water is supplied.

Since these equations are not solved for each demand site in one iteration, it is important to keep track of the actual withdrawal, and the required withdrawal that is not yet met. This is done using the following equations:

$$ACTUAL\_withdrawal_{sect} = TOT_{sect} + supply_{sect} \tag{2.31}$$

$$REQ\_withdrawal_{sect} = REQ\_withdrawal_{sect} - supply_{sect} \tag{2.32}$$

where TOT_{sect} contains the total actual withdrawal, for each demand site. The required withdrawal is updated by subtracting the actual withdrawal of that calculation step. WatCAM loops through these equations until either the available water ($TOTAL\_ava$) or the total required water ($sum(REQ\_withdrawal_{sect}, \dots)$) reaches zero.

In order to correctly determine the unmet demands, it is important to calculate the actual delivered water, based on the actual withdrawal. This delivered water is the same flux as the projected demand described earlier. Not only the delivered water is calculated, but the amount of consumed and returned water are also calculated using the following equations (corresponding to the concept presented in Figure 2.4:

$$DELIVERED\_water_{sect} = \frac{ACTUAL\_withdrawal_{sect}}{CONS\_F_{sect} - 1} \cdot REU_{sect} + 1 \tag{2.33}$$

$$CONSUMED_{sect} = DELIVERED\_water_{sect} \cdot CONS\_F_{sect} \tag{2.34}$$

$$RETURN_{sect} = DELIVERED\_water_{sect} - CONSUMED_{sect} \tag{2.35}$$

$$UNMET_{sect} = GROSS\_dem_{sect} - DELIVERED\_water_{sect} \tag{2.36}$$

where again, all equations are solved for each demand type.

Finally, the withdrawn water needs to be extracted from the available water, and other bookkeeping calculations need to be performed:

$$FLO\_extracted = min(ACTUAL\_withdrawn\_TOT, FLO\_ava) \tag{2.37}$$

$$RES\_extracted = min(ACTUAL\_withdrawn\_TOT - FLO\_extracted, RES\_ava) \tag{2.38}$$

$$\begin{aligned} GWT\_extracted = min(ACTUAL\_withdrawn\_TOT - FLO\_extracted - \\ RES\_extracted, GWT\_ava) \end{aligned} \tag{2.39}$$

$$RES\_inflow = min(FLO\_ava - FLO\_extracted, RES\_capacity - RES\_storage) \tag{2.40}$$

$$FLO\_out = FLO\_ava - FLO\_extracted - RES\_inflow + RETURN\_tot \tag{2.41}$$

$$RES\_storage\_new = RES\_storage - RES\_extracted + RES\_inflow \tag{2.42}$$

$$GWT\_storage\_new = GWT\_storage - GWT\_extracted + GWT\_inflow \tag{2.43}$$

$$\begin{aligned} BAL = FLO\_total - (CONSUMED\_tot + FLO\_out) - \\ (RES\_storage\_new - RES\_storage) - \\ (GWT\_storage\_new - GWT\_storage) \end{aligned} \tag{2.44}$$

where it is visible that the extracted water is extracted from each water source in a particular order. It is assumed that the water is firstly extracted from the surface water supply, than from the reservoirs and lastly from the groundwater. The remainder of the surface can be used as inflow into the reservoir. Outflow of the water province takes the return flows into account. Next, storage values for the reservoir and groundwater are updated. Finally, the water balance is calculated, to make sure that there has not been any errors in the calculations.

All these calculations occur within one time step, except the first three initial equation: these are only to initiate the reservoir and groundwater reservoirs.

3 Segura case study

In order to gain better understanding about WatCAM, the model was first applied to a basin with sufficient observations, as a case study. For this case study, the Segura basin in south-east Spain was selected. This basin was chosen, because there is a lot of data available and the basins is currently already experiencing water shortages. In this chapter, a short basin description is given. Next, the methods used to calibrate WatCAM are presented, followed by the results and discussion.

3.1 Short basin description

The Segura basin is situated in the south eastern part of Spain. The basin has a surface area of 18,930 km^2. The average precipitation ranges from 300 mm year^{-1} in the southeastern parts to 1000 mm year^{-1} in the higher located headwaters. The potential evapotranspiration averages around 1400 mm year^{-1}. The Segura River and all of its tributaries have a total length of 1,553 km (permanent and intermittent streams). Irrigation demand accounts for the biggest fraction of the total demand (85% in 2007), and due to the relatively low water availability, the gap between water supply and demand is rather large (Galiano, 2015).

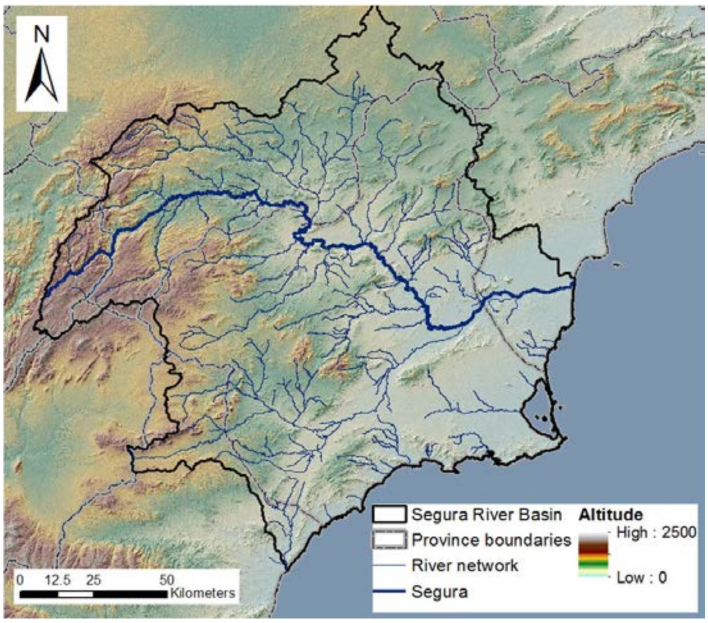

Figure 3.1: Overview of the Segura river basin, situated in southeast Spain (Galiano, 2015).

3.2 Methods

In the original WatCAM setup, the Segura basin was not defined as a single basin: it was a part of a bigger water province. This WP consisted of the Segura and the Jucar basin. However, sufficient data was available for only the Segura basin. As a result, the choice was made to split original water province into two temporary new water provinces: one containing the Jucar basin, and one containing the Segura basin. For this case study, only the Segura WP is investigated.

In order to correctly simulate the Segura basin, the input data needed to be altered. Input data from the original water province was altered, so that the yearly average of the first 10 years (2006-2015) matched the observations. In this section, the used data is described. The changes in data will be described in the following paragraphs.

3.2.1 Reservoir and groundwater capacity

To determine the reservoir capacity, the website of the Confederación Hidrográfica del Segura was consulted. Here, an overview of all reservoirs is given, together with the potential storage capacity. The total value of $1{,}140 \cdot 10^6$ m^3 was used for the total reservoir capacity (Confederación Hidrográfica del Segura, 2016).

The groundwater capacity is however, way more uncertain and difficult to measure. No good observations are available, covering the entire basin. As a result, the maximum groundwater capacity is assumed to be 1 m of water across the total area of the river basin: resulting in a value of $18{,}930 \cdot 10^6$ m^3. The groundwater inflow and outflow fractions (GWT_RECH and GWT_MAX, respectively) where changed so that the values matched values determined by Alonso & Aróstegui (2014). In this paper, a figure shows the groundwater extraction (both sustainable and unsustainable). Here the groundwater inflow (GWT_RECH) in matched with the sustainable groundwater extraction rate, and the ground extraction (GWT_MAX) is matched with the total groundwater extraction.

3.2.2 Internal, external and evapotranspiration

The internal flow was altered using again the ratio between the observed yearly average and the average of the original file. Now, the observed value of $704 \cdot 10^6$ m^3 $year^{-1}$ was used to alter the original time series (Confederación Hidrográfica del Segura, 2013). The historical flow was altered using the same fraction as used for the internal flow. The external flow for the business as usual scenario was not altered, because this new WP will only be ran with the Tagus WP enabled as well.

Reference evapotranspiration was given in mm $year^{-1}$, so there was no need to alter this value. WatCAM calculates that to m^3 based on the surface area.

For the external flow, the fraction of outflow of the upstream water province (Tagus) was altered, so that the values matched the observed values. A water transfer is present between the Tagus and the Segura river basins, and this fraction is trying to mimic this transfer. However, since it is only possible to define the fraction of water that is transferred to the Segura basin, one has very little control over the absolute amount of transferred water. This fraction is implemented for natural water transfers, making the simulation of non-natural water transfers very difficult. No changes were made in the original files, since this fraction is calculated dynamically, based on the water allocation in that particular water province.

3.2.3 Irrigation, domestic, industry and environment.

The irrigated area was corrected using data from Contreras & Hunink (2015). In this study, the irrigated area is calculated and presented per sub-region of the Segura basin. These values were summed and a total area of $2{,}580 \cdot 10^6$ m^2 was determined.

The population was also altered for the Segura. Again, data from Contreras & Hunink (2015) was used. Here the average population spanning 10 years was used. The original time series was altered, so that the average of the first 10 years corresponded to the observations. By using a ratio, the expected population growth for each SSP scenario was not affected. The domestic water requirement per capita was changed in such way that the WatCAM output corresponded to the observed values by Contreras & Hunink (2015).

The industrial demand was also. The original time series was changed with a factor, so that the average value of the first 10 years corresponded to the values presented by Contreras & Hunink

(2015). Again, by using this method, the expected changes over time where not affected. The same was done for the environmental demand, only with using values from Confederación Hidrográfica del Segura (2013).

3.2.4 Parameters

The parameters used for the Segura case study can be found in Appendix B.1 . As described above, the parameters where changed so that the modelled values matched the observed values.

3.3 Results

Using the altered data as described above, WatCAM was run for the Segura. The upstream water province (Tagus) was also ran, to ensure that the external flow was simulated correctly. The Segura WP has been ran for multiple different scenario combinations. In this section, the two most extreme scenario combinations are presented: RCP2.6 + SSP1 and RCP8.5 + SSP3.

3.3.1 Scenario analysis

In Figure 3.3, the water balance for the Segura WP is presented. The top figure shows the results of the RCP2.6 + SSP1 scenario, where the bottom plot shows the results of the RCP8.5 + SSP3 scenario. These are the most optimistic and most dramatic scenario combinations, respectively. The first scenario combination shows that the internal flow stays relatively equal in the first three periods, but shows an increase in the final period. External flow shows roughly the same pattern, due to the fact that the same climate pattern is present in the upstream water province. In this last period, PCR-GLOBWB expects an increase in precipitation, leading to a higher internal and external flow. The internal flow corresponding to the RCP8.5 scenario shows a gradual decrease, meaning that while the evaporation increases, the precipitation decreases[1]. The same response is visible in the external flow.

The sum of all demands for the RCP2.6 + SSP1 scenario stayed rather constant throughout the future. However, unmet demand seems to decrease in the last period, resulting from the increase in internal generated flow. In Figure 3.3, the projected (gross) and unmet demands are presented for each demand site, giving more insight in the distribution of water. Here it is clearly visible that the irrigation is the biggest demand site in the Segura basin. For the RCP2.6 + SSP1 scenario, the irrigation demand is rather constant throughout the entire simulation period. Looking back to the equations in Section 2.5, the irrigation demand is the product of the irrigated area and the reference ET. Here, the irrigated area is a constant, meaning that the reference ET should also be constant. This is not the case in the RCP8.5 + SSP3 scenario, where the irrigation demand increases. Again, irrigated area is constant, meaning that the reference ET is expected to increase. In both scenarios, the domestic, industry and environment contribute only for a very small amount to the total demand. As a result, the biggest unmet demands are also within the irrigation sector.

With the RCP2.6 + SSP1 scenario combination, domestic demand is expected to increase, and decreases slightly in the final period (2080-2099). However, the domestic demand is decreasing in every period for the RCP8.5 + SSP3 scenario. In the SSP1 scenario, the population is expected to increase up until 2050. From then on, the population decreases. SSP3 predicts, however, a population decrease already starting in the 2020s. This increase in population does not only affect the domestic demand, but also the industrial demand. Spain is expected to reach higher GDP

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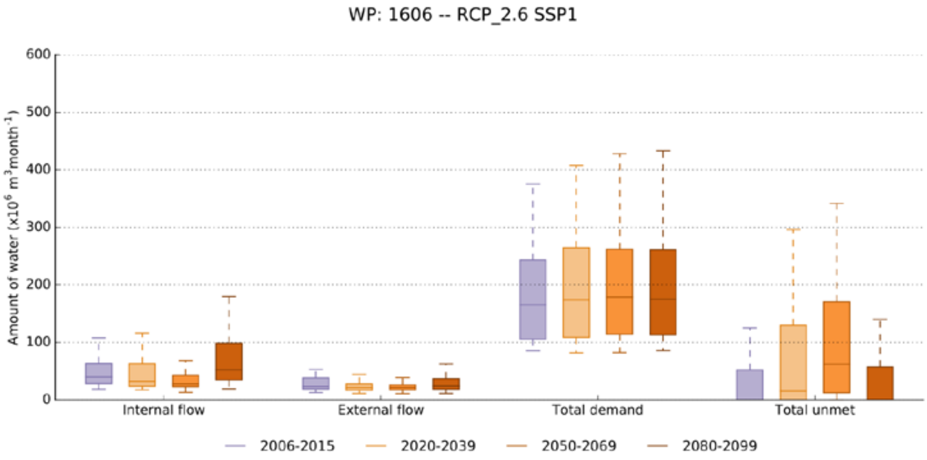
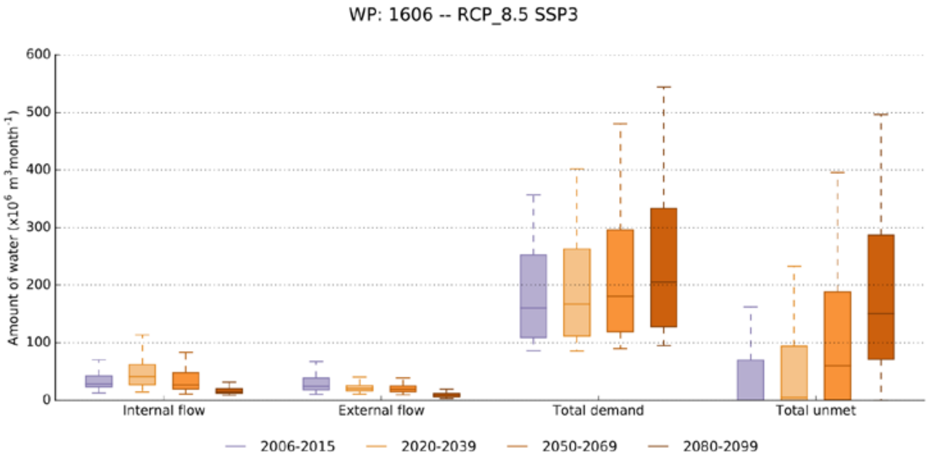
[1] Please note that the internal flow is an output of PCR-GLOBWB, WatCAM only reads these values as input.

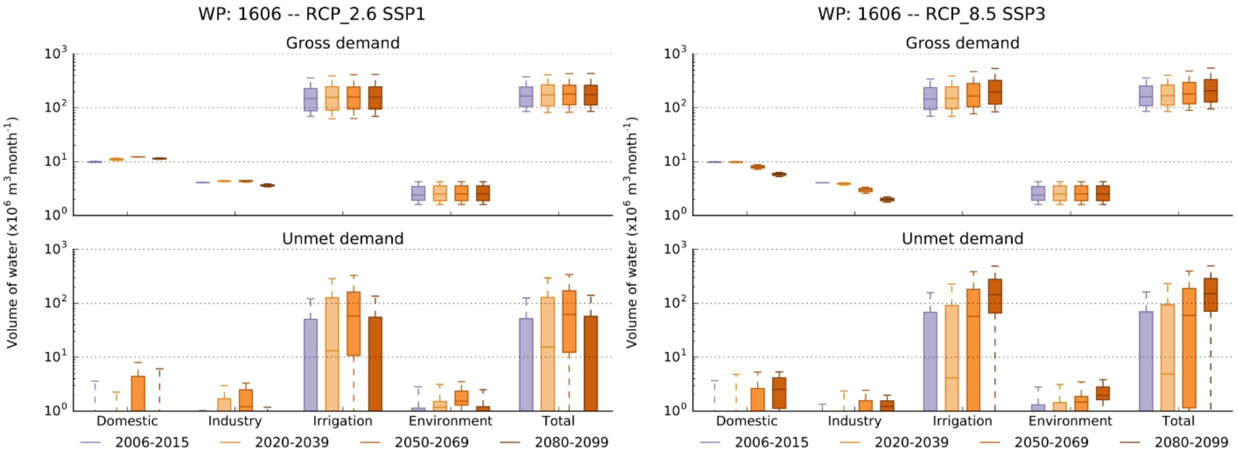


(a): Water balance of the Segura, using the RCP2.6 and SSP1 scenario



(b): Water balance of the Segura, using the RCP8.5 and SSP3 scenario

Figure 3.3: Internal and external flow, and the total and unmet demand for the Segura water province, presented for two extreme scenario combinations



(a): Gross and unmet demands using the RCP2.6 and SSP1 scenarios

(b): Gross and unmet demands using the RCP 8.5 and SSP3 scenarios

Figure 3.3: Projected (gross) and unmet demands for each sector. The downstream demand is left out, because no downstream demand is present in this WP. Please note that the Y axis of the unmet demand graphs ends at 1. Because of the presence of zeroes in the results, box plots are distorted on their lower parts.

Table 3.1: Yearly average values (in 10^6 m^3) calculated for each period, presented for the two extreme scenario combinations.

RCP 2.6 + SSP1												
			Gross demand					Unmet demand				
Period	Internal	External	DOM	IND	IRR	ENV	Total	DOM	IND	IRR	ENV	Total
2006-2015	718	754	119	49	2,067	32	2,267	1	4	398	6	409
2020-2039	690	361	139	55	2,230	34	2,458	11	10	832	12	864
2050-2069	564	304	154	55	2,272	34	2,515	25	17	1,173	20	1,235
2080-2099	1,255	568	143	46	2,216	34	2,439	4	4	483	7	499
RCP 8.5 + SSP3												
2006-2015	490	577	118	48	2,051	32	2,250	2	4	465	7	479
2020-2039	832	398	123	49	2,235	34	2,441	5	6	669	10	691
2050-2069	614	364	101	37	2,528	34	2,700	15	10	1,242	18	1,285
2080-2099	425	129	73	25	2,899	34	3,031	32	15	2,184	27	2,258

values in the future for both scenarios. The GDP per capita will increase with an increasing GDP and a decreasing population, making the water province less demanding in the industrial sector (according to Equation (2.2)). All of the values described above, and presented in the two figures, can be found in Table 3.1.

3.3.2 Water marginal cost curves

For this water province, the adaptation strategies were also analyzed. These adaptation strategies are related to certain costs. By using this information, it is possible to generate “Water Marginal Cost Curves” (WMCC). These WMCC show the amount of extra water available plotted on the x-axis, and the cost per m^3 is plotted on the y-axis. The WMCC for this water province can be found in Figure 3.4. The default values originating from Brandsma et al., (2015) were used, in order to determine the adaptation strategies. As a result, the price may not be representative for each water province: in some water provinces it might be cheaper to build a reservoir than in other water provinces. Since the aim of this case study is to gain more insight in WatCAM, the choice was made to not alter these costs. A more detailed description of the WMCC is described by Brandsma et al., (2015).

The adaptation strategies can be found in Table 3.2, where the changes and their costs are presented. This table can explain the behavior as seen in Figure 3.4. Since the irrigation is the sector demanding most water, increasing the consumed fraction together with decreasing the irrigated area results in an effective water saving measure. Increasing the reservoir is even more effective, but – as mentioned before – the costs and feasibility are questionable in this WP. Increasing the reuse in the irrigation sector, as well as in the domestic and industry sector has very little impact. Since the reuse fraction is already high for irrigation, this measure only increases the fraction by a small amount. Furthermore, since the domestic and industrial demands

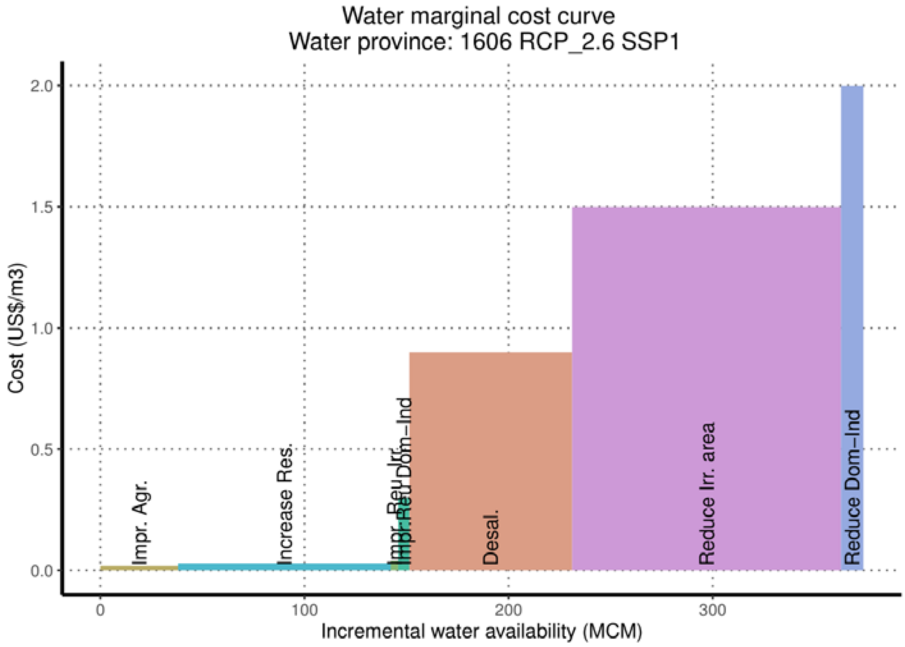


Figure 3.4: Water marginal cost curve for the Segura water province. Each color indicates a different adaptation strategy, presented from the cheapest to the most expensive strategy.

Table 3.2: Adaptation strategies and their changes to parameters, based on Brandsma et al. (2015)

Adaptation number	**Name**	**Measure**	**Costs (US$/m^3)**
Adpt_0	None	Normal/current situation	0
Adpt_1	Improved agriculture	Irrigation consumed fraction increased by 40% (0.82 -> 0.892), irrigated area reduced by (0.82/0.892), so that volume consumed remains equal	0.02
Adpt_2	Increase reservoir capacity	Add 1000 MCM to reservoir capacity	0.03
Adpt_3	Improve reuse irrigation	Increase irrigation reuse fraction by 50% (0.95 -> 0.975)	0.04
Adpt_4	Improve reuse dom+ind	Improve domestic and industry reuse by 60% (0.7 -> 0.88)	0.3
Adpt_5	Desalinization	Desalinate 100 MCM per year	0.9
Adpt_6	Reduce irrigated area	Reduce irrigated area by 10%	1.5
Adpt_7	Reduce dom+ind demand	Reduce domestic and industry demand by 15%	2

are relatively small, an increase in fraction of reused water results in a very small amount of saved water. Desalinization is an effective, yet expensive measure. Even more expensive, is the reduction of irrigated area, since this will most likely lead to less production and farmers demanding a compensation. However, this does result in a large amount of incremental water availability. Since irrigation demands so much water in this WP, a reduction in irrigated area results in a high amount of extra water availability (since less water is required). Finally, a reduction in domestic and industry demand is the most expensive measure, and has very little influence in this area; due to the fact that domestic and industry demand relatively low amount of water, compared to irrigation.

4 Global analysis

In this chapter, the results of multiple global WatCAM simulation runs are described. The results are first compared to other studies using a similar approach as this study. Next, a problem arising from this comparison is described and a solution is proposed. Finally, the global results using the latest version of WatCAM are presented. For all results presented in this chapter, the same scenario combination is used: RCP4.5 + SSP2. Both scenarios (climate and socio-economic change) are between the most extreme cases (see Section 2.4). This choice was made, in order to gain better understanding about what might happen in the future, without focusing on an extreme case.

4.1 Comparison to other studies

Gassert et al. (2014) determined the amount of blue water across the globe, using the AQUEDUCT tool. They defined the amount of blue water as the runoff generated within the area plus the runoff of the upstream areas. This definition is equal to the definition of internal plus

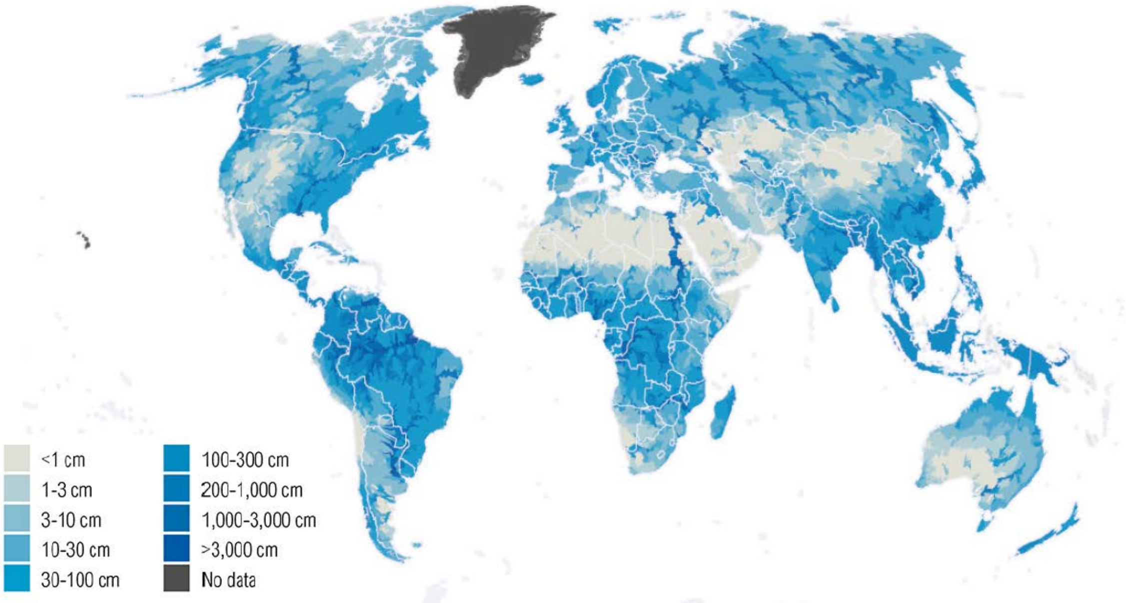


Figure 4.1: Total blue water as determined by Gassert et al. (2014). Values are in cm year^{-1}.

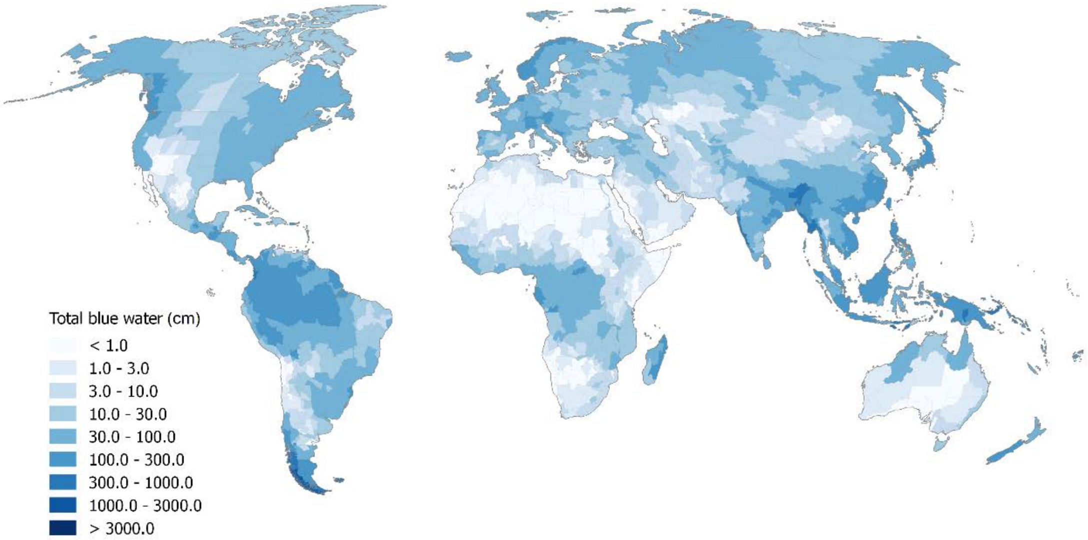


Figure 4.2: Total blue water (internal + external flow) as calculated by WatCAM. Values are in cm year^{-1}.

external flow used in the WatCAM. The amount of blue water as presented by Gassert et al. (2014) can be found in Figure 4.1. In Figure 4.2, the sum of internal and external flow is plotted. At first glance, it seems like results from WatCAM are lower than the results from Gassert et al. (2014). However, both results are corrected for the size of the simulated area. The areas used by Gassert et al. (2014) are smaller than the water provinces used in WatCAM. As a result, the high values visible in Figure 4.1 (e.g. Nile and Amazon rivers) are not as clearly visible as in Figure 4.2. The global pattern simulated by WatCAM does coincides with the pattern simulated with AQUEDUCT.

Using the same AQUEDUCT tool, Gassert et al. (2014) also determined the amount of withdrawn water, see Figure 4.3. These are withdrawals only performed for human use (domestic, industry and/or irrigation). The same figure is made for the WatCAM results, see Figure 4.3. Here, values are again corrected for the size of the area. The pattern and absolute values seem to have a very good match between the two different studies: India and China have the highest withdrawn values, together with parts of Western Europe, and some parts of North America. The values computed by WatCAM seem to be a little bit higher than the AQUEDUCT values: mainly visible

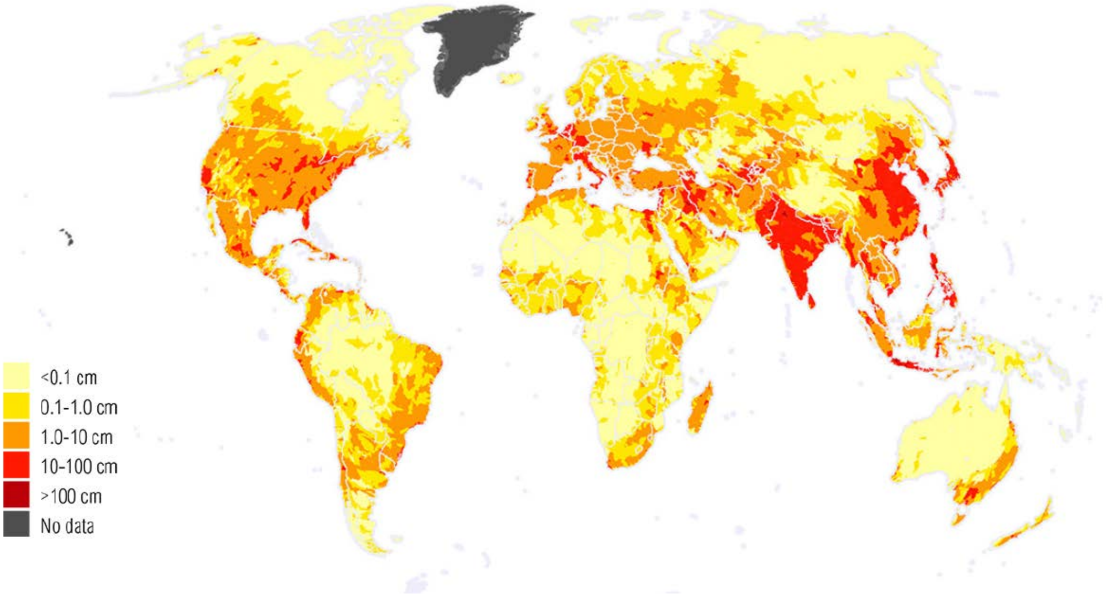


Figure 4.3: Total water withdrawn as calculated by Gassert et al. (2014). Values are in cm year^{-1}.

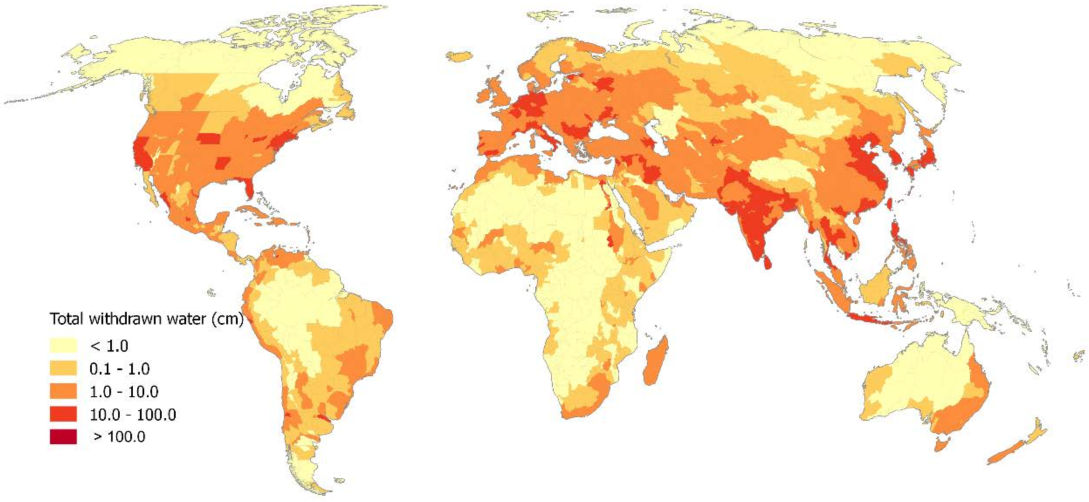


Figure 4.4: Total water withdrawn as calculated by WatCAM. Values are in cm year^{-1}.

in the northern hemisphere. Investigating the water withdrawn per sector, shows that industry is the biggest demand sector in those regions. One could conclude that WatCAM might be projecting a loo high industrial demand in these areas.

The high withdrawals of industrial water is also visible in the following two pictures. In Figure 4.5, the fraction of the total withdrawn water (excluding the environment) withdrawn for industrial uses is plotted (Tramberend et al., 2015). The same ratio is plotted in Figure 4.6, using results from WatCAM. These figures clearly show that the ratio between industrial withdrawn and total withdrawn water is too high in the northern hemisphere. Most likely, this is caused by using different ways in order to determine the demand for this industrial sector. The model used by Tramberend et al. (2015) takes energy and electricity demand, economic development and technological changes into account. In WatCAM, industrial demand is fully dependent on the gross domestic product (GDP) and population.

FAO (2015) investigated the amount of renewable water that is withdrawn for each country. The same ratio was calculated using results from WatCAM. Here it is assumed that all water flowing through the river (internal and external flow) can be seen as renewable water resources, since this water is originating from precipitation. Values from FAO were calculated on country scale, so results from WatCAM were accumulated per country in order to make a better comparison. In Figure 4.7 and Figure 4.8, results from FAO and WatCAM are presented, respectively. The global

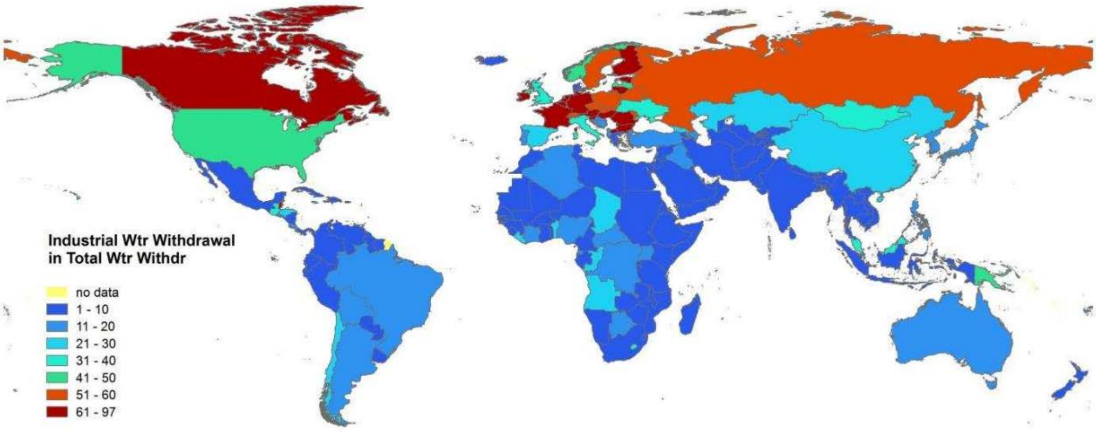


Figure 4.5: Fraction total withdrawn water used for industry, as presented by Tramberend et al. (2015)

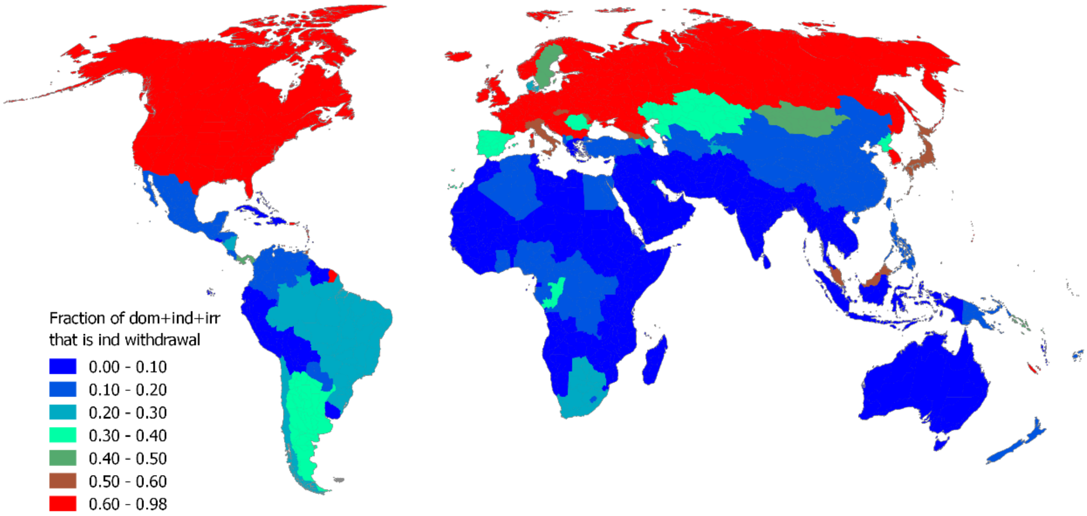


Figure 4.6: Fraction of total withdrawal going to the industrial sector, as simulated by WatCAM.

pattern seems to correspond good, however, absolute values seems overall lower than in the FAO study. In the North Africa and Middle East region, WatCAMs results seem to be lower than in the FAO data. China and Kazakhstan are in the 0-10% range in the WatCAM results, but in the FAO are both countries in the 10-25% range. The origin of these differences can have different causes. Biggest differences are most likely the result of using different methods in order to determine the amount of available, required and withdrawn water, and are a result of using different values to determine the index value.

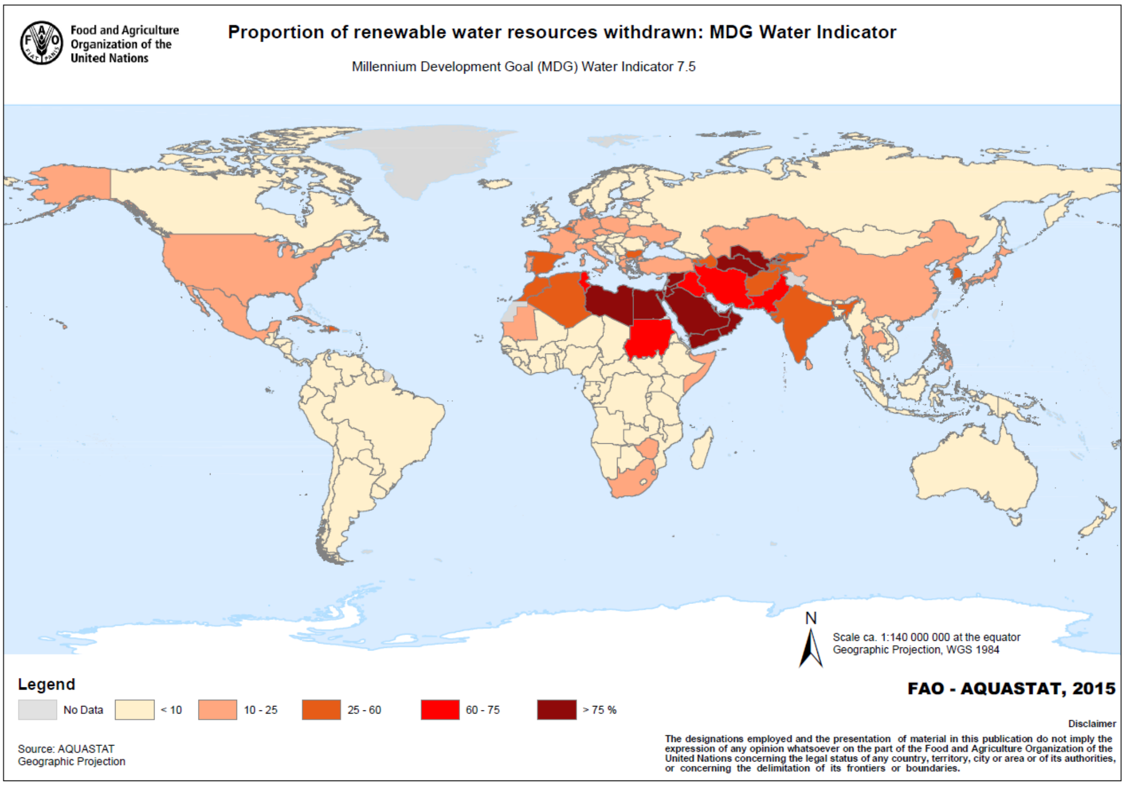


Figure 4.7: Percentage of renewable water that is extracted as a result of anthropogenic use (domestic, industry and irrigation). Higher values indicate more stress on the water system (FAO, 2015).

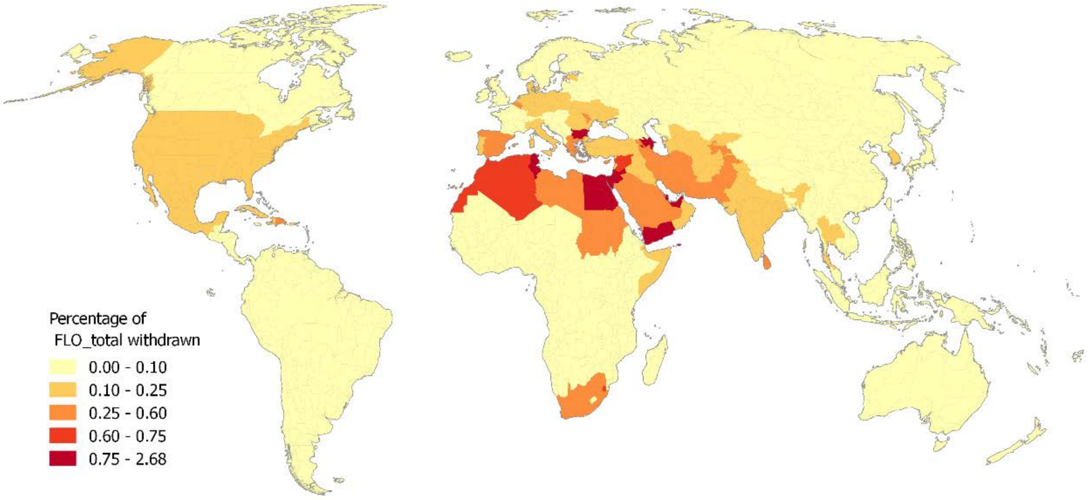


Figure 4.8: Percentage of total flow (internal + external flow) withdrawn, as calculated by WatCAM. Values are based on the average over the baseline period (2006-2015).

4.2 Groundwater reservoirs

4.2.1 Problem description

During the comparison with other studies, remarkable behavior was observed within the groundwater part of WatCAM. During the model run over the entire period (2006-2099), groundwater reservoirs seemed to move to one of two extremes: either completely full or completely empty. The percentage of groundwater capacity that is filled and the end of the simulation period (averaged over 2080-2099) is plotted in Figure 4.9. This figure shows that groundwater reservoirs are either completely full of completely empty in this period, while all groundwater reservoir are initially filled for 70%. This problem can be caused by multiple factors: wrong calculations of the groundwater recharge, wrong calculation of the groundwater outflow, or an error in the groundwater capacity. Currently, the recharge is a set fraction of the internal flow. The maximal groundwater extraction is a fraction of the storage at that time step, and the groundwater capacity is a fixed number. All of these values are rather uncertain, and are prone to contain errors. It was not clear how the current maximum groundwater capacity values were determiner (was not described by Brandsma et al. (2015)).

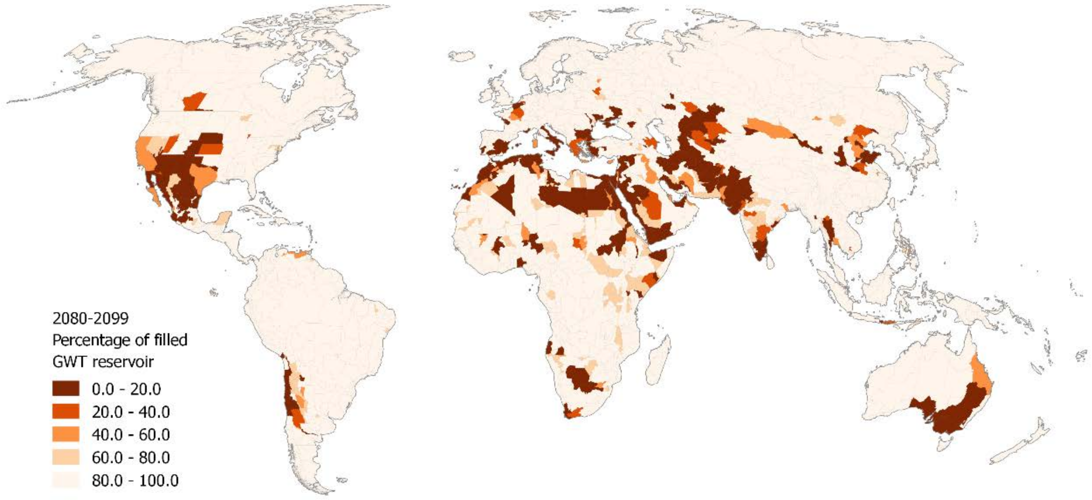


Figure 4.9: Percentage of the full groundwater capacity that is filled with water at the end of the simulation period, as calculated by WatCAM.

4.2.2 Solution

In order to fix this problem, the choice was made to alter the groundwater concept. Firstly, the groundwater capacity was removed, and groundwater reservoirs were given ‘infinite’ storage. Furthermore, the amount of recharge and maximum amount of extraction within each time step was altered. Each change is described below.

By removing the maximum groundwater capacity, it is no longer possible for the groundwater reservoirs to fully deplete. Groundwater storage is now initialized at 0 m^3. Any changes are added or subtracted from this value. However, to prevent groundwater reservoirs from filling up to unrealistic amounts, any value above 0 m^3 is being diverted back into the river at the end of the time step. We assume here that the value of 0 m^3 represents a full groundwater reservoir, and infiltration is no longer able. As a result, groundwater storage values are not able to get above 0 m^3. When groundwater is extracted, this value becomes negative.

The internal flow, as received from the PCR-GLOBWB model, consist of three components: direct runoff, runoff from second store, and baseflow. We assume that the monthly baseflow is equal to

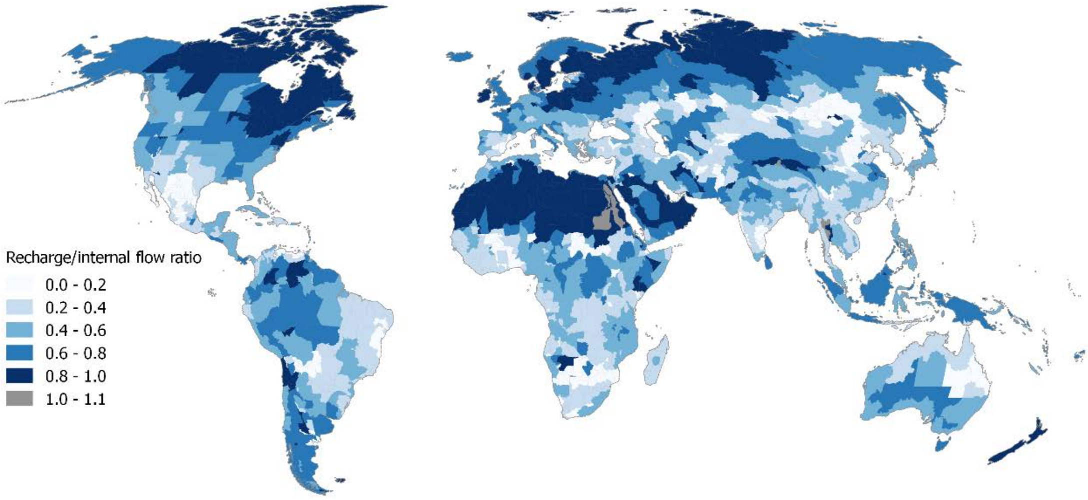


Figure 4.10: Ratio between groundwater recharge and internal flow, using the new groundwater calculations.

the monthly recharge. Recharge is a quicker process than the baseflow, but since WatCAM operates at a monthly time step, differences are expected to be small. It is still possible to change the amount of recharge, since the *GWT_RECH* parameter is still present: representing the groundwater recharge as a fraction of the simulated baseflow (default value = 1).

Effects of this new addition can be found in Figure 4.10. In this figure, the ratio between groundwater recharge and internal flow is plotted. Using the original WatCAM equations, this ratio was determined by the *GWT_RECH* parameter; resulting in a value of 0.05 across the globe (the default value for *GWT_RECH*). With this new addition, this ratio is higher in almost every area. Largest differences are in the northern parts of the Northern Hemisphere, and in the Middle East – North Africa region, where the recharge/internal flow ratio is almost equal to 1. This implies that almost all surface water is transferred to the groundwater reservoirs, before it is available for (anthropogenic) withdrawals. In a few areas (the Nile for example) the recharge/internal flow ratio is higher than one, meaning that the baseflow is higher than the total internal flow. This is possibly the effect of groundwater reservoirs spanning across multiple water provinces, but which are not linked within the WatCAM simulation. The amount of recharge was adjusted by the internal flow, to make sure that the groundwater recharge did not exceeded the internal flow.

Finally, the maximum amount of extractable groundwater was changed. Previously, it was dependent on the current storage of the groundwater reservoirs, but since groundwater reservoirs can contain infinite amount of water (theoretically), this is no longer possible. In the new version, the maximum groundwater extraction is based on the average recharge. The average recharge is calculated over the baseline period (2006-2015) and is multiplied with a certain fraction (GWT_MAX). This parameter is defaulted to 2, meaning that the maximum extraction at each time step is limited by two times the average recharge during the baseline period. This does mean however, that groundwater reservoirs can, theoretically, supply infinites amounts of water, only limited at each time step.

4.2.3 New groundwater equations

Below, all equations that received changes due to this new implementation are presented.

Firstly, the initial groundwater storage is changed (replacing equation (2.5)), so that the initial values equals to zero:

$$GWT\_storage = 0 \tag{4.1}$$

Equation (2.9) was changed: instead of using a certain fraction of the internal flow as groundwater recharge, the baseflow (output from PCR-GLOBWB) is used. This file is read in advance as input file, and is implemented in WatCAM using the following equation:

$$GWT\_inflow = GWT\_baseflow * GWT\_RECH \tag{4.2}$$

where GWT_inflow represents the groundwater recharge, $GWT\_baseflow$ the baseflow as calculated by PCR-GLOBWB, and GWT_RECH a correction factor in the case when the end user has good knowledge about the recharge in the area of interest. This parameter has a default value of 1.

Next, the maximum extraction rate needs to be determined, which is based on the average recharge during the baseline period. This is done using the following equation, replacing Equation (2.12):

$$GWT\_ava = (RECH\_average * GWT\_RECH) * GWT\_MAX \tag{4.3}$$

where GWT_ava is the potential groundwater outflow (maximum extraction), based on a fraction (GWT_MAX) of the average recharge during the baseline period ($RECH\_average$). Please note the presence of GWT_RECH parameter in this equation. By default, this value is set to 1, but when the end user has sufficient knowledge/data about the groundwater recharge, he can choose to increase or decrease the groundwater recharge using this fraction. As a result, the average recharge needs to be influenced by this fraction as well.

At the end of the time step, after the water allocation process, small changes are made to the final calculations. The following equations replace all equations after Equation (2.40):

$$GWT\_storage\_new = GWT\_storage - GWT\_extracted + GWT\_inflow \tag{4.4}$$

$$GWT\_outflow = \begin{cases} GWT\_storage\_new, & GWT\_storage\_new > 0 \\ 0, & GWT\_storage\_new \leq 0 \end{cases} \tag{4.5}$$

$$GWT\_storage\_new = GWT\_storage\_new - GWT\_outflow \tag{4.6}$$

$$\begin{aligned} FLO\_out = {} & FLO\_ava - FLO\_extracted - RES\_inflow + RETURN\_tot \\ & + GWT\_outflow \end{aligned} \tag{4.7}$$

$$\begin{aligned} BAL = {} & FLO\_total - (CONSUMED\_tot + FLO\_out) - (RES\_storage\_new \\ & - RES\_storage) - (GWT\_storage\_new - GWT\_storage) \end{aligned} \tag{4.8}$$

Please note the new formula in this series of equations (Equation (4.5)). This equation determines whether there is a ‘natural’ outflow from the groundwater reservoir, only occurring when the groundwater storage values are positive. When this occurs, we assume that the groundwater reservoir is full, an all extra water is transported to the river at the end of the time step. As a result, the flow out of the water province gains an extra argument: $GWT\_outflow$.

4.3 Availability fraction based on population density

After this implementation, one more change was explored: adding a ‘water availability fraction’. The idea behind this fraction is that in very thin populated areas, not all water flowing through the river can be used by this population. In the denser populated areas, it is assumed that all water in the river can be used. This resulted in the following availability fraction, ranging between thinly populated areas and very dense populated areas. The values and ranges are presented in Table 4.1. Here, we assume that there is always at least 25% of the total water in the river available. At a population density of 200 inhabitants per km^2, we assume that the upper limit is reached, and that all water in the river is available to use. All population density values between these two limits are linearly interpolated, and population density values exceeding the upper limit receive the same availability fraction of 1. The assumption is that areas with a low population density do not have the recourses and capacity to make use of all water within the water province. Furthermore, if the water province is very large, and the population is centered on one location, it is unlikely that all water can (potentially) be used by this population.

Table 4.1: Minimum and maximum values for the availability fraction

Population km^{-2}	0	–	200
Availability fraction	0.25	–	1.00

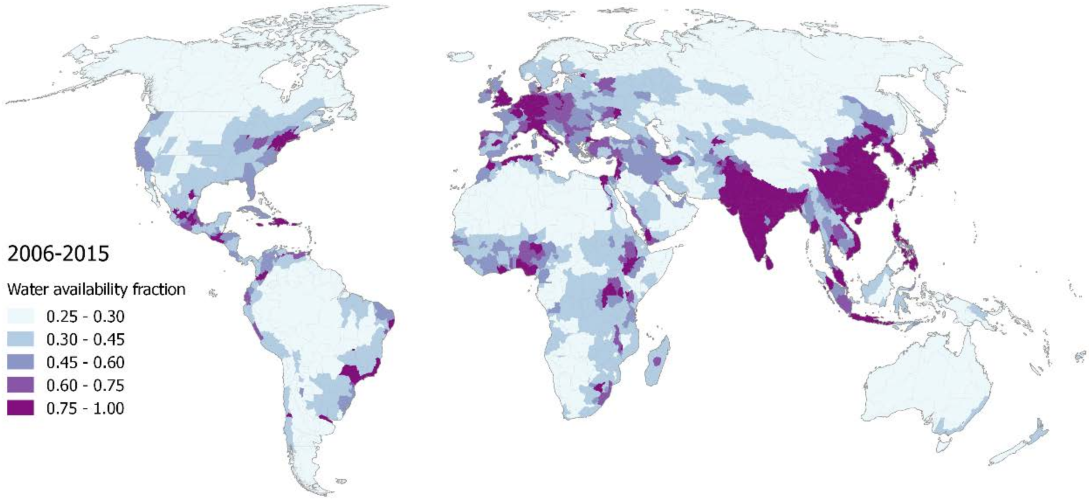


Figure 4.11: Water availability fraction, calculated as average over the baseline period (2006-2015)

In Figure 4.11, this fraction is plotted for every water province. This figure shows a high water availability fraction for the densely populated areas (China, India, Europe, etc.), as is expected. However, when comparing results from this version of WatCAM with the previous version of WatCAM, regarding water availability and unmet demand, only small differences were found. This addition to the model mostly influences areas with a low population density. However, areas with a low population density generally also have a low water demand. As a result, a reduction in water availability had very little influence on the unmet demand, for example.

Values chosen to use within this concept are very uncertain and it is questionable whether these are close to reality – also due to a lack of scientific research to base these values on. Since this addition had very little impact on the overall model results, the choice was made to exclude this concept from the final version.

4.4 Final global results

In this section, the result from the first final version of WatCAM are presented. WatCAM was again run for the entire globe, with the new groundwater concept and without the water availability index. Firstly, the gross demand is shown in Figure 4.12, as total sum in Figure (e), but also separated per demand sector. The domestic, industry, irrigation and environment demand values can be found in Figure (a) to (d), respectively. Downstream demand is set to zero in each water province, due to a lack of data, and is therefore not plotted.

Environmental demand is the highest demand sector, peaking in the naturally wet areas. Next, the irrigation and industry sectors demand the largest amounts of water. However, patterns within each demand sector are different for each demand sector. Industry demand is highest in Europe and the eastern parts of North America, but also China and Japan. Irrigation demand is highest in India and China (around Shanghai and Beijing), but is also high in the southern parts of Europe and North America, and in the area around Iran. Domestic demand is overall the smallest contributor to the total demand, yet it is still high in some areas: India, eastern China, Netherlands, England, and some countries in middle Africa.

The environmental demand sector is the highest in the wet areas, since WatCAM bases the demand on a fraction (20%) of the pristine flow; with a high pristine flow, the environmental demand will be high as well (see the Amazon River for example). Irrigation demand is determined by the amount of evapotranspiration and the size of the irrigated area. This figure depicts high irrigation demands in areas where the population is relatively high, and where the number of hours with sunshine is relativity high. Industrial demand is high in areas with a high GDP, as is expected from Equation (2.2).

In Figure 4.13, the sources of the extracted water are plotted. Per source, the amount of extracted water from that source is divided by the total amount of extracted water. The sum of the fractions for each source equals to 1 for any given water province. Please note that WatCAM uses a fixed order to extract water from the water supply: first from surface water, then from reservoirs, and lastly from groundwater. This same order is used to present these figures: surface water in (a), reservoirs in (b) and groundwater in (c). In this figure, it is clearly visible that the surface water contributes for the largest amount to the total extracted water. This is partly due to the order of allocating water, but also due to the fact that the other two water sources are dependent on the amount of internal flow (≈ surface water). Reservoirs have the overall smallest fraction contributing to the total discharge, since reservoirs are not present in each water province. However, in the south western part of North America (e.g. California, Colorado, parts of Mexico), reservoirs supply relatively large amounts of water. In these regions, WatCAM simulates a buffering effect by the reservoirs, where the reservoirs are getting filled during wet periods, and water is extracted during dry periods. Groundwater contribution sits between reservoirs and surface water contribution; being more important in the drier regions. In these areas, a larger fraction of the internal flow is being transported to the groundwater before being available to extract (see Figure 4.10). As a result, less surface water is available, making more extraction from groundwater inevitable. In Appendix C.1 , the same figures can be found, but for the most distant future period.

The three figures in Figure 4.13 give an indication of the pressure on the water systems across the globe. Generally, extraction from surface water is seen as sustainable extraction, since this water is renewable (precipitation). However, extraction from groundwater can either be sustainable or unsustainable, dependent on the amount of recharge. In this study, it is assumed

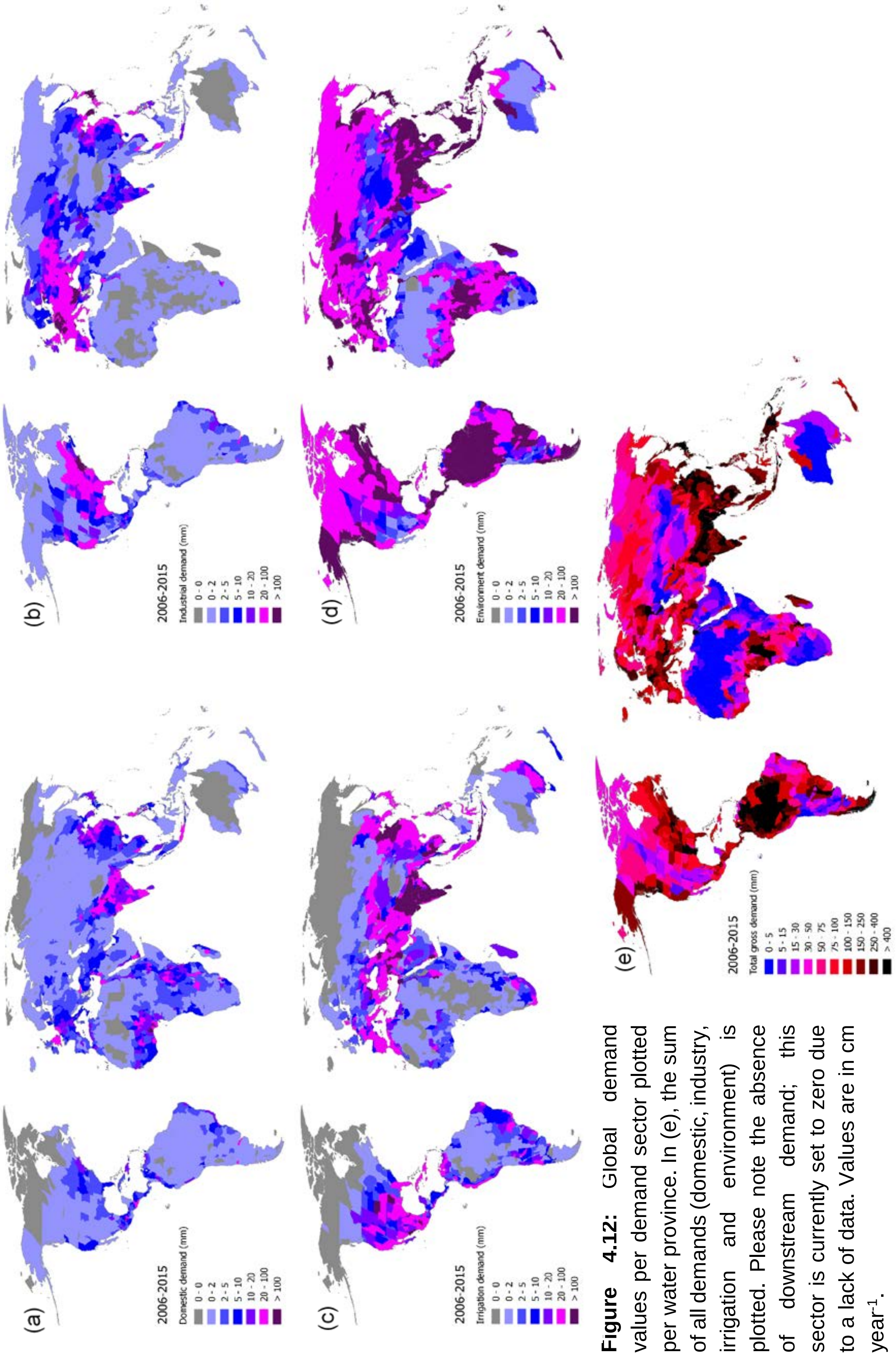
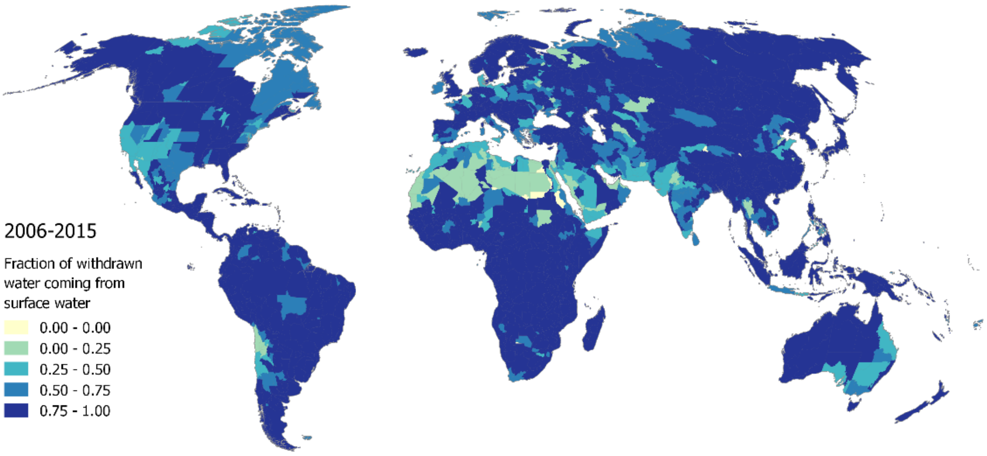
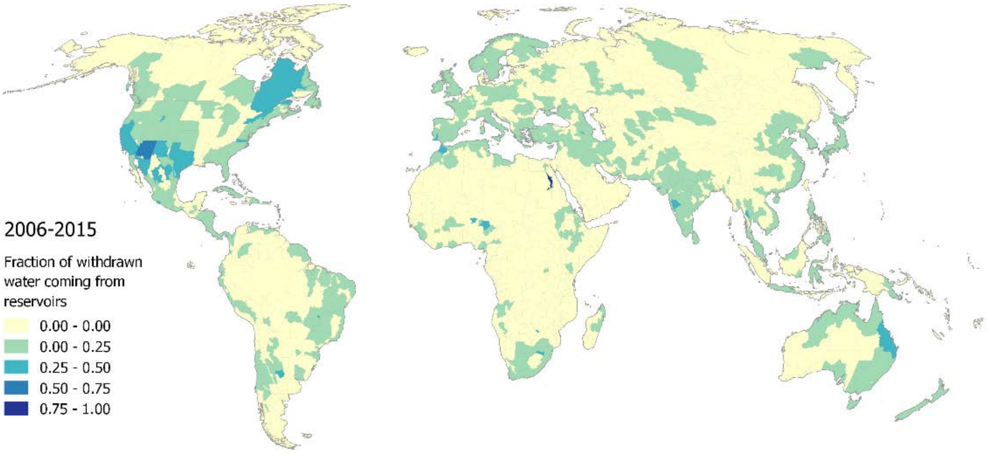


Figure 4.12: Global demand values per demand sector plotted per water province. In (e), the sum of all demands (domestic, industry, irrigation and environment) is plotted. Please note the absence of downstream demand; this sector is currently set to zero due to a lack of data. Values are in cm year^{-1}.

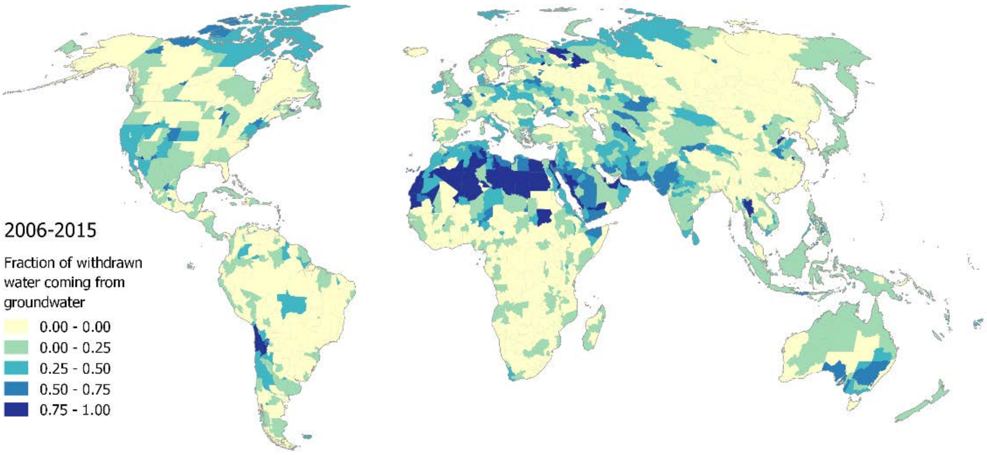
that the amount of recharge can be seen as renewable (and thus sustainable) groundwater extraction, and extractions higher than the recharge are unsustainable, since the groundwater volume decreases. In Figure 4.14, the ratio between groundwater extraction and groundwater recharge is plotted. A value of 1 indicates groundwater extraction equal to the groundwater



(a): Fraction of supplied water originating from surface water



(b): Fraction of supplied water originating from reservoirs



(c): Fraction of supplied water originating from groundwater

Figure 4.13: Source of the supplied water. Sources can be: surface water, reservoirs and/or groundwater; figure (a) to (c), respectively. A value of 1 indicates that all extracted water is originating from that particular source.

recharge. Values smaller than 1 indicate groundwater extraction smaller than the recharge, while values larger than 1 indicate more groundwater extraction than recharge. From this figure, it is visible that in some areas around the globe, the current situation already relies on unsustainable

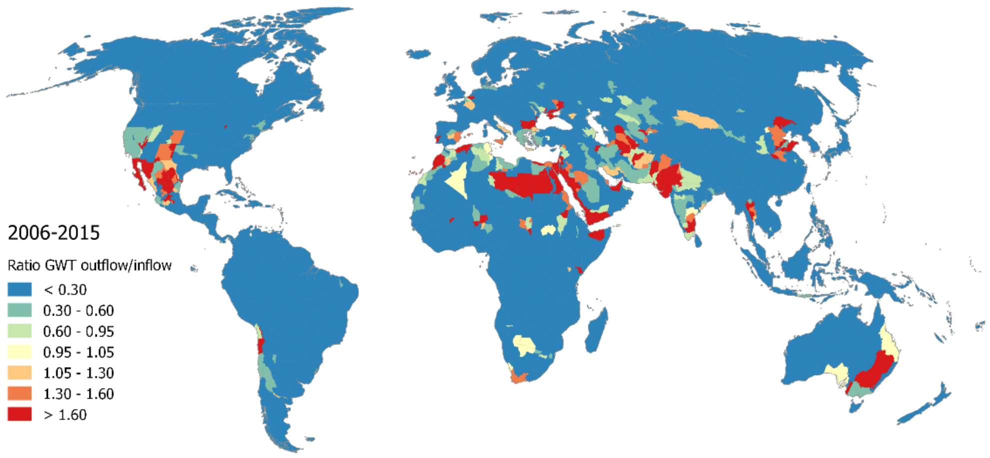


Figure 4.14: Ratio between groundwater extraction and recharge. Values are averaged over the baseline period. Blue colors indicate areas where groundwater outflow is lower than the recharge, while red values indicate the opposite.

groundwater extraction. In the future, this is only expected to get worse, since the amount of available water drops, and the gross demand is not expected to decrease. This same figure has been made for a future scenario, and it is clearly visible that the number of areas relying on unsustainable groundwater extraction is only expected to increase (see Appendix C.2).

The effect of unsustainable groundwater extraction is also visible as the change in groundwater volume. In Figure 4.15, the decrease in groundwater volume is plotted, both for the current situation (2006-2015) as for a future scenario (2080-2099). Please note that these values are a decrease in groundwater volume (water column), based on the area of the water province. These values do not represent a decrease in groundwater level, since one would need information about the specific yield and the actual size of the groundwater reservoir. Since groundwater volumes are only allowed to be negative, no positive values are shown here. Groundwater volumes which do not have changed (remained at 0 m^3) are assumed to be stable; receiving more recharge than there is water extracted. From these figures, it is clear that the already present pressure on groundwater reservoirs is only expected to increase in the future[1]. In these areas, it would be wise to invest in some adaptation strategies, in order to make use of the groundwater reservoirs in a more sustainable way.

This unsustainable use of groundwater reservoirs is caused by a relatively too large demand. As a result, WatCAM tries to meet the demand by extraction a lot of groundwater. However, in some areas, the unmet demand is inevitable: both for the current situation as for the future situation. In Figure 4.16, the unmet demands are plotted for both the baseline and a future period. Please note that these unmet demand values are plotted in percentages: the percentage of gross demand that is unmet. This ensures that the unmet demand is in ratio with the gross demand: the impact of an unmet demand of e.g. 5 mm is dependent on the gross demand value. Here it is clearly visible that countries which are already depending on unsustainable groundwater extraction and thus reducing the groundwater volumes, also have an unmet demand. Both relations are not unexpected, since using groundwater in an unsustainable way is caused by

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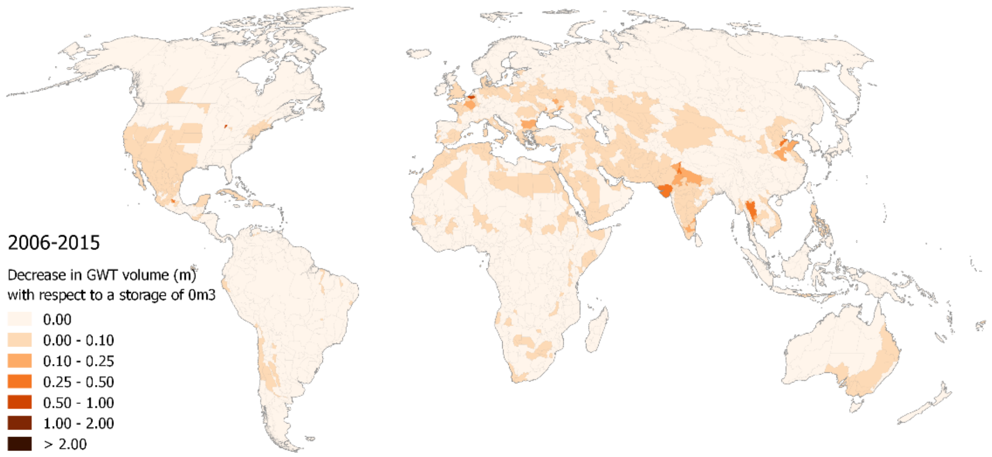
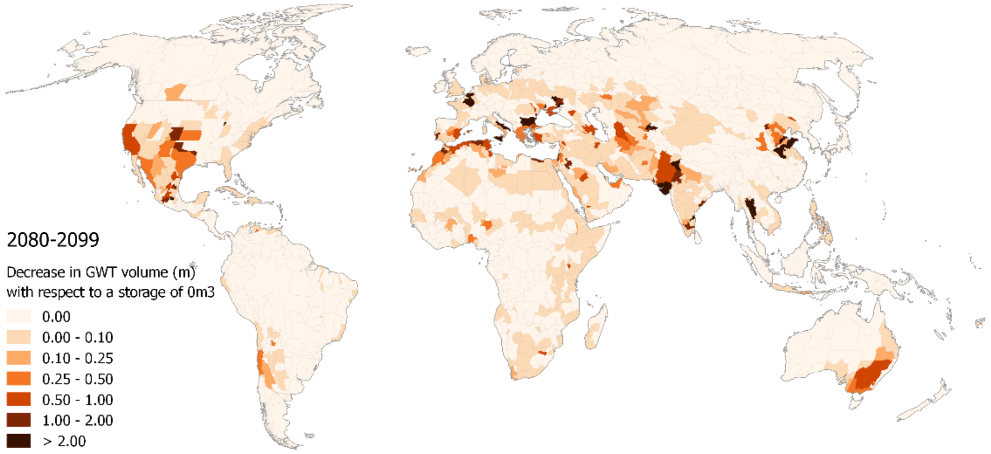
[1] A few water provinces (Belgium and a part of Illinois, USA) show odd results. Both water provinces have very high industrial demand. It is recommended to change these values to more realistic numbers when investigating these areas in more detail.



(a): Average decrease in groundwater volume at the baseline period.



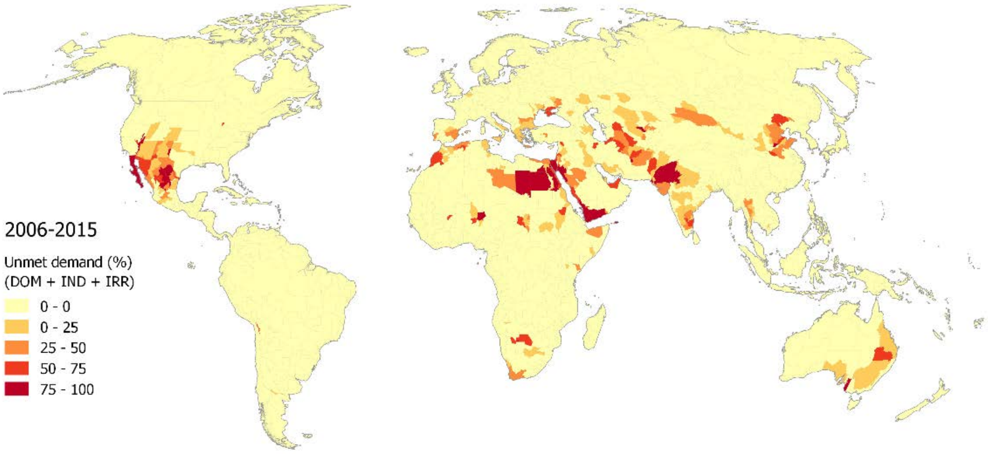
(b): Average decrease in groundwater volume expected during the 2080-2099 period.

Figure 4.15: Average decrease in groundwater volume, with respect to a 'full' capacity of 0 m^3, for both the current situation and a future scenario, using RCP4.5+SSP2

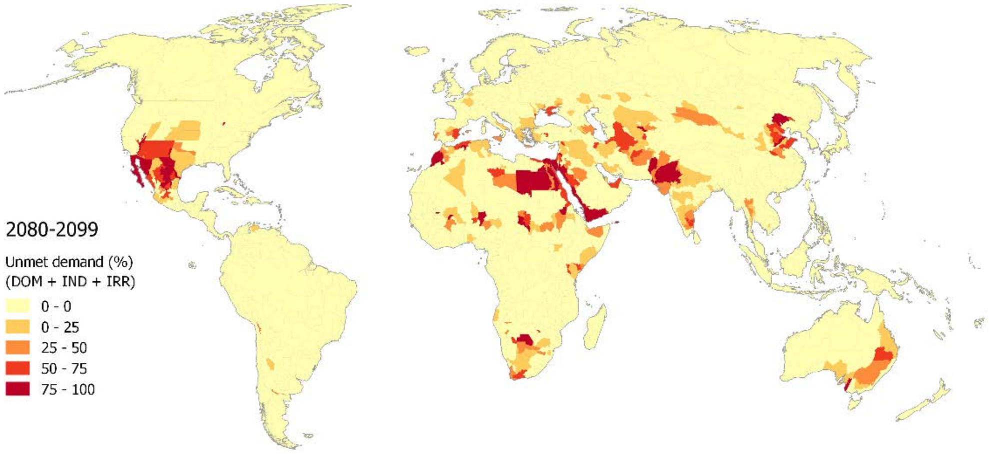
(relatively) large demand values. All water provinces with an unmet demand (current or expected) are very likely able to reduce this unmet demand by applying some adaptation strategies.

Below, in Table 4.2, the global values are presented (in km^3), averaged over each corresponding period. These values are summed for each water province. Here it is visible that the internal flow stays relatively equal during the entire simulation period, only seeing a decrease of 200 km^3, globally. Please note that these values are globally summed values, and the regional patterns might differ. As a result of this decrease, less surface water is available (FLO_ava), and thus less surface water is extracted. Furthermore, the amount of extracted reservoir water has been decreased from 394 km^3 to 363 km^3. Reservoirs can only be refilled by surface water, and since this value has decreased, the average storage capacity in the reservoirs has been decreased as well. Therefore, less water can be extracted from the reservoirs. Since less water is extracted from both the surface water and the reservoirs, more groundwater needs to be extracted: increased from 816 km^3 to 1,032 km^3 in the first and last period, respectively.

The total demand values seem to decrease in each future period. However, the domestic, industry and irrigation sectors require more water in the future. Only the environment is demanding less water. This is due to the fact that environmental demand is limited by 20% of the total flow. With



(a): Unmet demand during the baseline period.



(b): Unmet demand during the 2080-2099 period.

Figure 4.16: Percentage of gross demand that is unmet, for both the current situation and a future scenario, using RCP4.5+SSP2. Only the unmet demand for the domestic, industry and irrigation sectors is presented. Since the same priorities are used for every WP, this pattern is fixed for every demand sector.

a lower internal flow – and thus also total flow – this limited will be reached more often, reducing the environmental demand. Domestic demand seems to increase by more than 250%: as a result of rapidly growing population. Industrial demand seems to increase up until around 2060, and decreases in the final period. Irrigation demand is only expected to increase in the future: resulting from a higher evapotranspiration. Overall, the environment is the biggest demand sector.

The total unmet demand is expected to increase in the future: from 573 km^3 year^{-1} in the current situation, to 868 km^3 year^{-1} in the last period. This unmet demand is mostly caused by the unmet demand in the agricultural sector. Unmet irrigation demand ranges from (roughly) 500-750 km^3 year^{-1}, while each other sector has unmet demands ranging from 10-50 km^3 year^{-1}. The environment has the largest demand values, but has relatively very low unmet demand volumes. Since environmental demand is high in areas with naturally high river discharges, sudden high unmet demands are unlikely. As described earlier, irrigation occurs in areas with a lot of sunlight hours; and these areas more prone to have higher unmet demand values due to higher ET values.

Table 4.2: Global values for available and extracted water, as well as the (gross) demand and unmet demand values. All values are in km^3 year^{-1}, averaged over the corresponding period.

Period	Internal flow	Available surface water	Extracted surface water	Extracted reservoir water	Extracted groundwater
2006-2015	44,538	59,240	15,374	394	816
2020-2039	44,446	57,285	15,059	348	956
2050-2069	43,507	55,207	14,632	358	1,021
2080-2099	44,339	56,841	14,586	363	1,033
			Demand		
	Domestic	Industry	Irrigation	Environment	Total
2006-2015	172	919	2,740	13,553	17,384
2020-2039	261	978	2,872	13,189	17,300
2050-2069	376	992	3,021	12,699	17,087
2080-2099	454	948	3,098	12,608	17,107
			Unmet demand		
	Domestic	Industry	Irrigation	Environment	Total
2006-2015	10	31	509	23	573
2020-2039	20	44	605	28	697
2050-2069	35	54	701	32	822
2080-2099	47	54	733	34	868

5 Conclusion

This study was carried out to improve and further develop the Water and Climate Adaptation Model (WatCAM). This tool was designed to provide sensible predictions about changes in future water availability and demand on the regional or global level, and study adaptation strategies.

Before WatCAM was applied, the model was translated from Excel to Python. Resulting from this translation, errors and inconsistencies were fixed. Larger changes were made as well; the demand & supply concept was improved, in order to make this more realistic with the available data. The translation of model ensured that the model became more transparent, computationally efficient and easier to improve when necessary.

Next, WatCAM was applied to the Segura River basin, for which sufficient data on water resources are available. Based on these data, WatCAM was calibrated. This calibration gave great insight in the operation of WatCAM and the most import parameters. In this area, the biggest demand for water is originating from irrigation. Multiple scenario combinations were ran for the Segura water province. By choosing the two most extreme scenario combinations, it became clear that (the already present water gap of 400 MCM) is expected to increase in the future; even with the most optimistic scenario combination (ranging between 1,170 to 2,180 MCM). The adaptation strategy analysis showed that – with the default adaptation measures – this water cap is too large to close. Due to the large demand by irrigation, improving this sector would yield the biggest improvements. One important aspect to keep in mind, is that both the adaptation measures as the costs are almost certainly different for each region around the globe (including this water province), due to different conditions.

A comparison between results from WatCAM and other similar studies, showed that WatCAM is able to simulate comparable results. There are however, some differences, and thus opportunities to improve WatCAM: mainly regarding the industrial demand values. A problem related to the groundwater reservoirs arose, and was fixed by removing the physical maximum capacity. Furthermore, the groundwater recharge and maximum outflow were altered, making the groundwater section of WatCAM behave more realistically. With this new addition, groundwater reservoirs can no longer completely deplete. As a result, unmet demands are no longer caused by empty groundwater reservoirs. Next, another possible change to the model was explored: adding a water availability fraction, based on the population density. However, since differences with a run without this fraction were small, and because the values one would need to define for this fraction are very uncertain and prone to have errors, the choice was made to exclude this fraction from the final version of WatCAM.

An analysis from the global results of the latest version of WatCAM, showed that each water demanding sector has a different global pattern. Domestic demand is highly dependent on the population, industrial demand is highly dependent on the economy, irrigation on the population and evapotranspiration and the environmental demand on the (undisturbed) discharge of the river. Environmental demand is overall the largest demand sector. Most of the supplied water is extracted from the surface water. Due to the fixed extraction order in WatCAM (surface water, reservoir, groundwater), this was not unexpected. The contribution of reservoirs is rather small, due to the fact that not all water provinces contain reservoirs to extract water from. Finally, groundwater contribution is highest in the drier countries, where most of the internal flow is used as groundwater recharge. Finally, results showed that some regions are already experiencing a water gap. Most of these regions are extracting more groundwater than there is recharging. This unsustainable use of groundwater leads to a reduction in groundwater volume (and thus in groundwater level). The unsustainable extraction of groundwater, decreasing groundwater volumes and unmet demands are not only expected to get worse in the areas already experiencing those problems, but are also expected to occur in more areas. In order to reduce these problems, adaptation strategies can reduce the water demand and/or water availability in these areas, and will thus reduce the unmet demand.

WatCAM is a great model to give a quick overview of the projected water availability and demand, given a certain scenario combination. The model has a large amount of parameters, making the model flexible for the end user: almost all values can easily be changed with a parameter. WatCAM can very quickly simulate multiple water provinces, given the user a good first look at the possibilities in that corresponding region. However, if the user desires a more detailed simulation of a certain region, it is advisable to use a different model, since WatCAM is designed as a global modelling tool.

6 Recommendations

In this chapter, recommendation regarding the model are presented, as well as recommendation for further studies.

- Anthropogenic water transfers are currently not properly implemented. In the current version of WatCAM, the user can only define a fraction of water that is going downstream, and not a fixed, absolute value. For natural transfers, a fraction is more realistic, but anthropogenic transfers are managed with e.g. a minimum and maximum transferred amount. In some areas (e.g. the Segura River Basin), anthropogenic transfers play a very important role.
- Currently, one fixed set of adaptation strategies is defined. Since these strategies and their costs are highly variable for each region, defining adaptation strategies per region/country would yield more realistic results. It is important that these adaptation strategies are ran within WatCAM from the least to the most expensive measure.
- Environmental demand and downstream demand coincide for some part. Water that is demanded by the environment but not consumed, is transported to the downstream water province anyway. The amount of water reserved for the downstream demand sector should be adjusted for this value. The same can be done for the return flows of the other demand sectors. However, it is important to keep the water quality aspect in mind when implementing this feature.
- Reuse of water between different demand sectors within one water province is not possible: all return flows are immediately transported downstream, while in reality, return flows from the domestic sector could be reused within the irrigation sector.
- Groundwater recharge and extraction is performed stepwise within one time step. Ideally this would happen more simultaneously.
- Groundwater reservoirs can currently supply infinite amounts of water, only limited at each time step. In reality, groundwater reservoir have a limited capacity. Since the data available for this study, was uncertain, groundwater capacities were removed. It would however, be more realistic to implement groundwater reservoirs with a maximum capacity, in order to achieve more realistic results.
- The equations determining the amount of industrial water need some improvement. The comparison with other studies showed that industrial demand (or withdrawal) values were too high in some regions of the world. In a few WPs, industrial demand values are way too high for the size of the region (e.g. Belgium and a part of Illinois).
- Both the irrigation consumed fraction as the correction factor are fixed in time. It is very likely that farmers will decide to used different crops or irrigation techniques when the water availability changes (Hanasaki et al., 2013). This can happen at any demand sector, while currently all fractions (consumed and reuse) are fixed in time.

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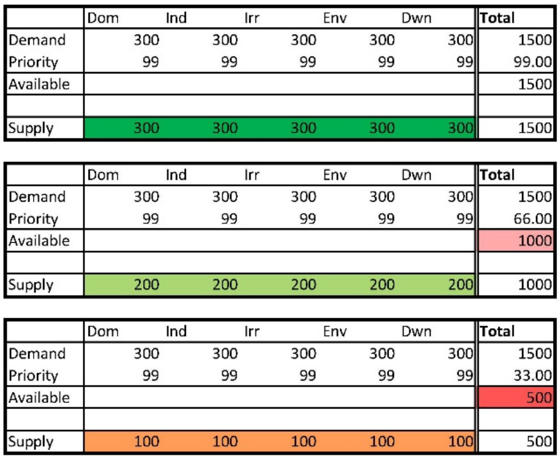
Appendix A WatCAM model concepts

A.1 Priority examples

Case 1 Priority 99



	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	99	99	99	99	99.00
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	99	99	99	99	66.00
Available						1000
Supply	200	200	200	200	200	1000

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	99	99	99	99	33.00
Available						500
Supply	100	100	100	100	100	500

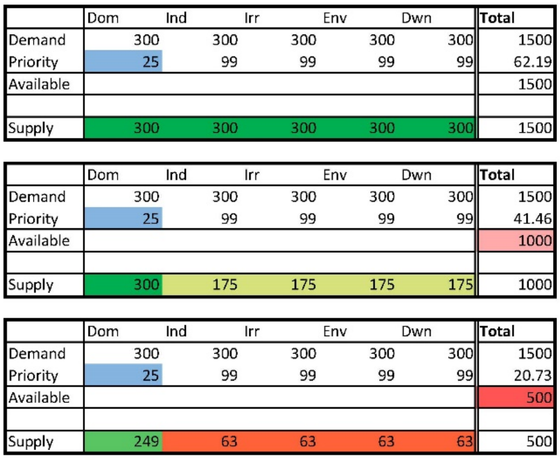
Case 2 Priority 1

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	1	1	1	1	1	1.00
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	1	1	1	1	1	0.67
Available						1000
Supply	200	200	200	200	200	1000

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	1	1	1	1	1	0.33
Available						500
Supply	100	100	100	100	100	500

Case 3 Domestic demand higher priority

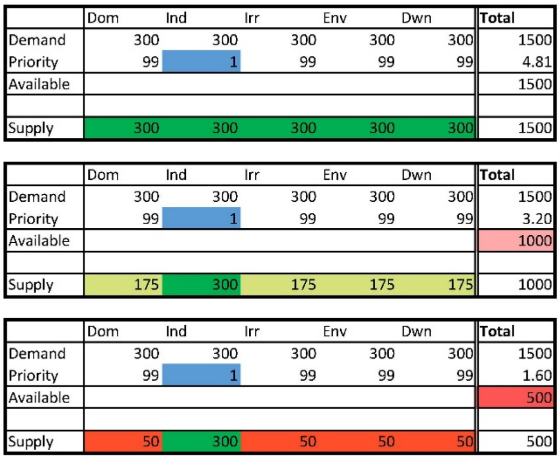


	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	25	99	99	99	99	62.19
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	25	99	99	99	99	41.46
Available						1000
Supply	300	175	175	175	175	1000

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	25	99	99	99	99	20.73
Available						500
Supply	249	63	63	63	63	500

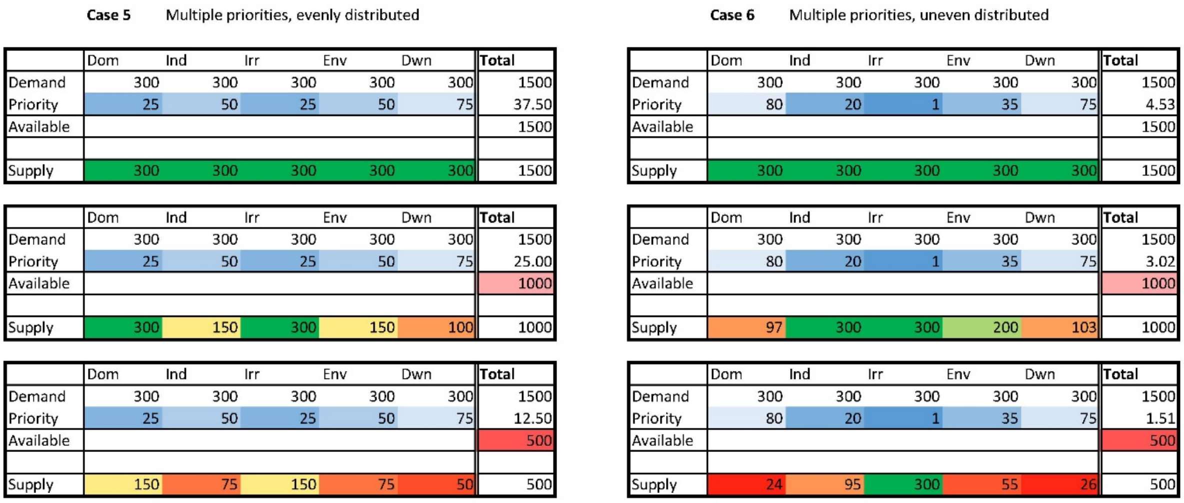
Case 4 Even higher priority



	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	1	99	99	99	4.81
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	1	99	99	99	3.20
Available						1000
Supply	175	300	175	175	175	1000

	Dom	Ind	Irr	Env	Dwn	Total
Demand	300	300	300	300	300	1500
Priority	99	1	99	99	99	1.60
Available						500
Supply	50	300	50	50	50	500



Case 5 Multiple priorities, evenly distributed

	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	25	50	25	50	75	37.50
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	25	50	25	50	75	25.00
Available						1000
Supply	300	150	300	150	100	1000

	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	25	50	25	50	75	12.50
Available						500
Supply	150	75	150	75	50	500

Case 6 Multiple priorities, uneven distributed

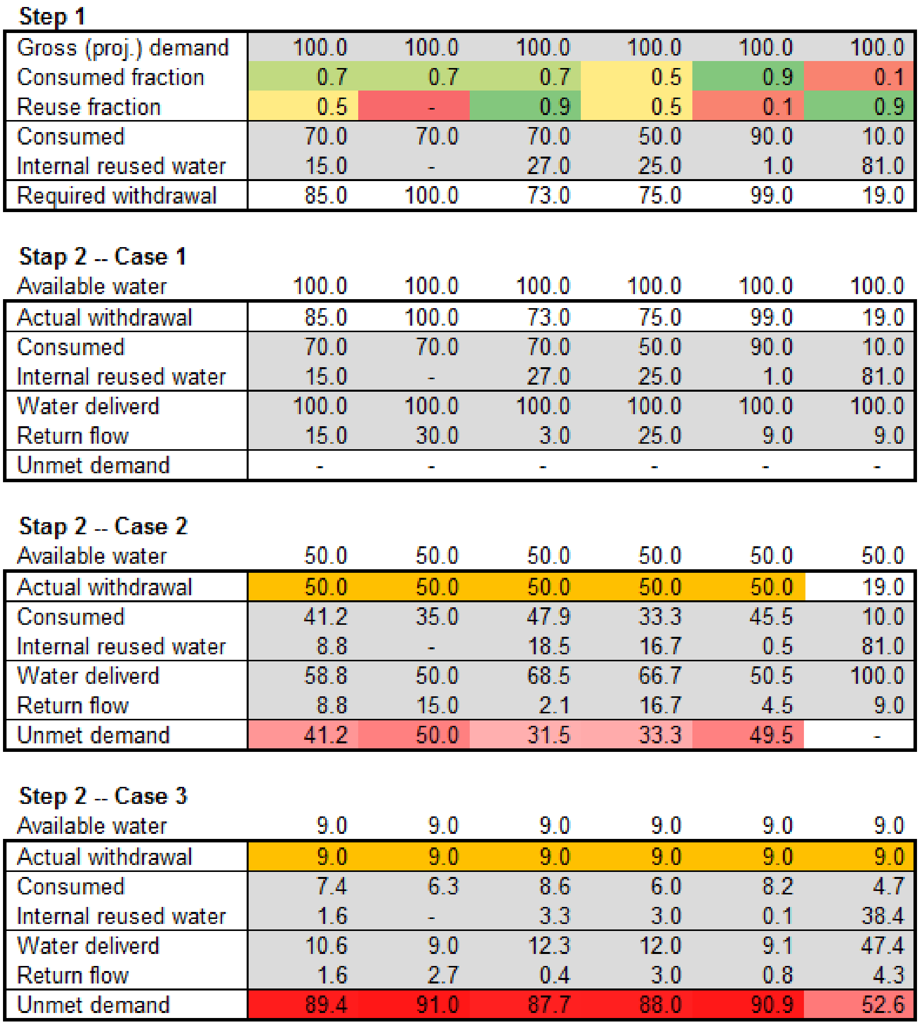
	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	80	20	1	35	75	4.53
Available						1500
Supply	300	300	300	300	300	1500

	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	80	20	1	35	75	3.02
Available						1000
Supply	97	300	300	200	103	1000

	Dom	Ind	Irr	Env	Dwn	**Total**
Demand	300	300	300	300	300	1500
Priority	80	20	1	35	75	1.51
Available						500
Supply	24	95	300	55	26	500

Figure A.1: Examples of the priority system, as implemented in WatCAM. Each case represents a different combination of priorities, resulting in different ways of allocating the water. The priority in the ‘Total’ column represents the *PRI_TOT* in the equations. In each case, three different possibilities are presented, always starting with enough available water, and each possibility down is with less available water.

A.2 Demand supply concept examples



Step 1

Gross (proj.) demand	100.0	100.0	100.0	100.0	100.0	100.0
Consumed fraction	0.7	0.7	0.7	0.5	0.9	0.1
Reuse fraction	0.5	-	0.9	0.5	0.1	0.9
Consumed	70.0	70.0	70.0	50.0	90.0	10.0
Internal reused water	15.0	-	27.0	25.0	1.0	81.0
Required withdrawal	85.0	100.0	73.0	75.0	99.0	19.0

Stap 2 -- Case 1

Available water	100.0	100.0	100.0	100.0	100.0	100.0
Actual withdrawal	85.0	100.0	73.0	75.0	99.0	19.0
Consumed	70.0	70.0	70.0	50.0	90.0	10.0
Internal reused water	15.0	-	27.0	25.0	1.0	81.0
Water deliverd	100.0	100.0	100.0	100.0	100.0	100.0
Return flow	15.0	30.0	3.0	25.0	9.0	9.0
Unmet demand	-	-	-	-	-	-

Stap 2 -- Case 2

Available water	50.0	50.0	50.0	50.0	50.0	50.0
Actual withdrawal	50.0	50.0	50.0	50.0	50.0	19.0
Consumed	41.2	35.0	47.9	33.3	45.5	10.0
Internal reused water	8.8	-	18.5	16.7	0.5	81.0
Water deliverd	58.8	50.0	68.5	66.7	50.5	100.0
Return flow	8.8	15.0	2.1	16.7	4.5	9.0
Unmet demand	41.2	50.0	31.5	33.3	49.5	-

Step 2 -- Case 3

Available water	9.0	9.0	9.0	9.0	9.0	9.0
Actual withdrawal	9.0	9.0	9.0	9.0	9.0	9.0
Consumed	7.4	6.3	8.6	6.0	8.2	4.7
Internal reused water	1.6	-	3.3	3.0	0.1	38.4
Water deliverd	10.6	9.0	12.3	12.0	9.1	47.4
Return flow	1.6	2.7	0.4	3.0	0.8	4.3
Unmet demand	89.4	91.0	87.7	88.0	90.9	52.6

Figure A.2: Examples regarding the demand and supply concept, as presented in Section 2.3. The first table represents the first calculation step, and the three tables below represent the second step. Each case of the second calculations uses a different amount of available water, in order to gain better insight in the effects on the unmet demand.

Appendix B Segura case study

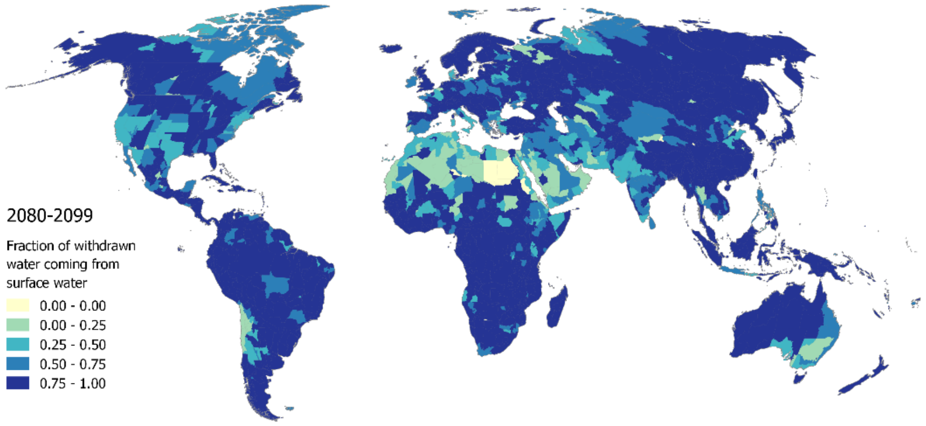
B.1 Parameters

Table B.1: Parameters used in the Segura case study

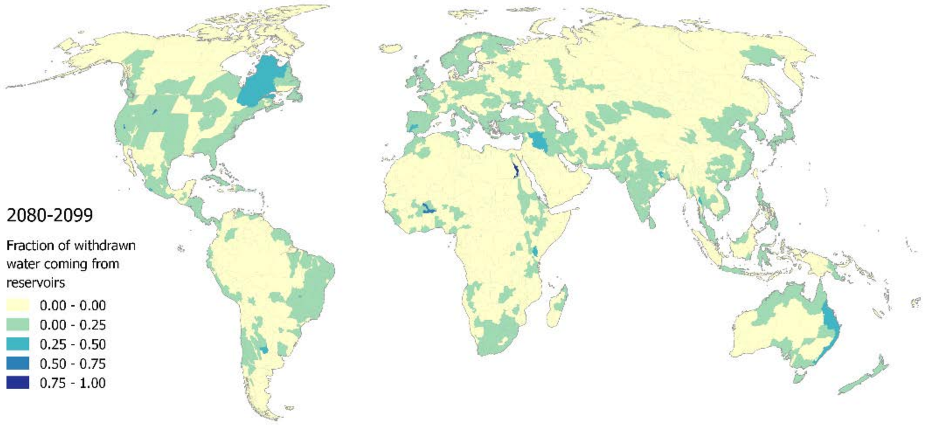
Name	Value	Name	Value
AREA_WP	18930	IND_CONS_F	0.8
Calibration	1.02	IND_DEM	1
DESAL	50	IND_PRI	15
DOM_CONS_F	0.8	IND_REU	0.7
DOM_PRI	10	INFORMAL	0
DOM_REU	0.7	IRR_AREA	1
DWN_DEM	0	IRR_CONS_F	0.82
DWN_PRI	50	IRR_COR	1.109209
ENV_FRAC	0.032	IRR_PRI	20
ENV_PRI	50	IRR_REU	0.95
ENV_USE	1	RES_extra	0
Ext_User	0	RES_INIT	0.8
GWT_INIT	0.8	RES_MAX	0.1
GWT_MAX	0.003	URB_DEM	1
GWT_RECH	0.15		

Appendix C Global analysis

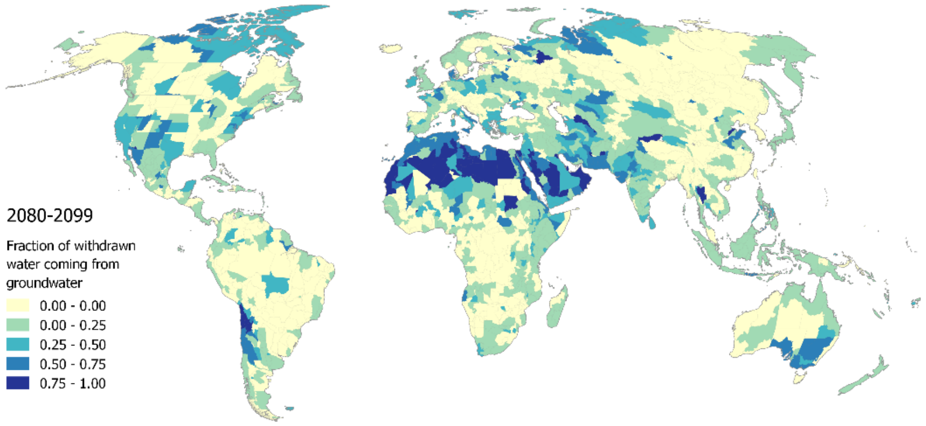
C.1 Source of supplied water in a future scenario



(a): Fraction of supplied water originating from surface water



(b): Fraction of supplied water originating from reservoirs



(c): Fraction of supplied water originating from groundwater

Figure C.1: Source of the supplied water in a future scenario (2080 - 2099, RCP4.5 + SSP2). Sources can be: surface water, reservoirs and/or groundwater; figure (a) to (c), respectively. A value of 1 indicates that all extracted water is originating from that

C.2 Groundwater extraction in the future

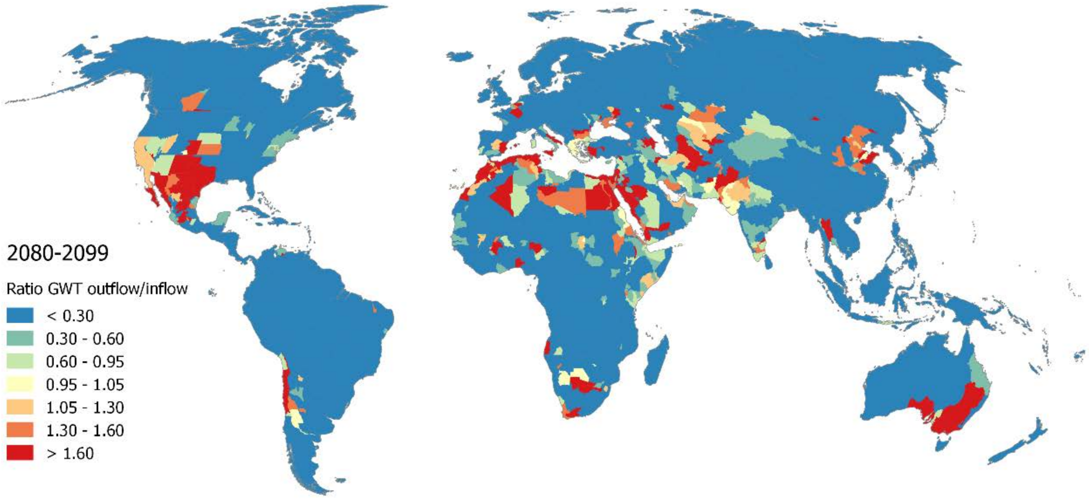


Figure C.2: Ratio between groundwater extraction and recharge. Values are averaged over 2080-2099. Blue colors indicate areas where groundwater outflow is lower than the recharge, while red values indicate the opposite.