



COFFEE CULTIVATION IN A
CHANGING CLIMATE
BACHELOR PROJECT

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Bachelor Spatial Planning and Design
Bachelor Project – Assignment 7, Final version
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Date: 15th of January, 2021

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1. Summary

About a 100 million people are dependent on the cultivation of coffee (Bunn *et al.*, 2015). The process of coffee production is one with a very high water footprint. Most of the water consumed is green water, but as a result of a changing climate it is suspected that there will be more blue water involved in the process of coffee production (Chapagain and Hoekstra, 2007). The aim of this research was to investigate how the water footprint of coffee production is affected by climate change. This is done by answering the research question “*How does climate change influence the water footprint of coffee production and what are the implications for future coffee production?*” By the use of different spatial and statistical analyses, it is concluded that the areas in which coffee cultivation can be executed will decrease significantly. Another process is that these areas are moving outside of the current coffee cultivating countries. The result is that many plantations will suffer from the changing climate, and that there should be looked into smart methods for coffee cultivation regarding water consumption and heat stress. This, to ensure the water footprint of coffee cultivation and production is brought down. Next to this, awareness should be raised about the water footprint of every cup coffee consumers consume.

2. Introduction

2.1 Background

A 100 million people are dependent on coffee production (Bunn *et al.*, 2015). The coffee crop is one of the crops that consumes the most water. It is calculated that for a cup of coffee in the Netherlands, on average 140 L water is consumed. The largest share of this water is not consumed in the Netherlands, but in the countries where the coffee is cultivated and produced, such as Brazil or Mexico (Chapagain and Hoekstra, 2007; Mekonnen and Hoekstra, 2011). A virtual water flow emerges when in some part of the world, there is a demand for water consumption somewhere else in that same world. Of the total water consumption, about 16% is covered by virtual water flows. Of this 16%, about 76% is related to agriculture, and mainly to crop production (Hoekstra and Mekonnen, 2012). Virtual water trade can either increase or decrease the global water consumption depending on the efficiency of the trade. This is related to the fact that countries with a low water productivity often are dependent on countries with a high water productivity. When there is a high water availability in a country with a high water productivity, this is efficient. With a low water availability in a country that has a high water productivity, one might wonder if this can be done more efficiently (Chapagain and Hoekstra, 2008; Hoekstra and Mekonnen, 2012).

2.2 Research problem

As stated before, a 100 million people are dependent on coffee and its production process and the livelihood of these people will very likely be negatively affected by the process of climate change. Where Arabica coffee already suffers from higher temperatures itself, also coffee pests will be able to spread quicker. The production of Robusta coffee will be harmed by larger variations in temperature, and a changing pattern in precipitation will influence the possibilities for coffee production, as of that there is a lot of water involved in the process of producing coffee. It is expected that less, or more extreme patterns in, precipitation will ensure that the blue water footprint increases, where the green decreases. The areas that are suitable for coffee production will probably change in the coming years, and therefore this research will look into the effects of climate change on the water footprint of coffee production, and the implications of this in coffee production in the future. The central question that this research aims to answer is: *“How does climate change influence the water footprint of coffee production and what are the implications for future coffee production?”*

To find an answer to this question, several aspects are investigated. To begin with, a picture of the locations of current coffee plantations is essential to start with the research. Sub-question 1 (S1) is derived from this: *“What are current locations for coffee production?”* It is also interesting to see whether there are, at this moment, locations for coffee productions which are not sustainable anymore. Therefore, sub-question 2 (S2) is the following: *“Which current locations for coffee production are not suitable for sustainable coffee production?”*. Next to this, sub-question 3 (S3) is relevant for the climate projections: regional climate projections of the current coffee-producing areas are necessary to be known to make an analysis on the sustainability of coffee production in the future. Thus, sub-question 3 is: *“What are climate projections for the current coffee-producing areas?”* From the first sub-question, a final sub-question can be constructed (S4): *“Which areas are likely to experience a decline in the sustainability of coffee production in the (near) future?”*

The research was focused on the cultivation of the crop, as it isn't be feasible in the given amount of time to include other parts of the coffee production process as well. There is looked into the climatic stressors that indicate whether or not coffee cultivation is sustainable in certain areas.

2.3 Structure of thesis

When reading this thesis, one will find a clear structure on the research and its process. In Chapter 2, a theoretical framework is created to create the basis for the research. Key terms are explained, and a conceptual model is created to show the connections between the different key terms. In the end of this chapter, hypotheses are drawn up. Chapter 3 will describe the methodological approach for this research. It will explain this research had a quantitative approach, the reasons for this approach, and the process of data collection and analysis. Chapter 4, the results, will be split up in multiple sub-chapters, each finding the main results for the different sub-questions and the main question that are composed in the Research Problem per area. In Chapter 5, conclusions will be drawn, and in Chapter 7 there will be a discussion on the shortcomings of the research, the findings are compared with existing literature, and recommendations for further research are given.

3. Theoretical Framework

The water footprint is a tool that can be used to quantify the amount of fresh water consumed in the production of a good. For an even better insight, a subdivision is created with three main components: the green, blue and grey water footprint. The green and the blue water footprint are related directly to freshwater consumption, where the grey water footprint is related to pollution of the water as a result of production processes. The green water footprint is the amount of rainwater consumed (or evaporated) in a production process. The blue water footprint is the amount of ground and surface water that is consumed (evaporated) in the production process. The blue water footprint tends to be higher in areas where there is a higher water scarcity. This can be related to the fact that in those areas, there is less green water available for consumption. The grey water footprint is the amount of fresh water that is needed to bring down the concentrations of pollutants in waste waters to acceptable levels. The use of fertilizers increases the grey water footprint, as it causes pollution of the ground and waste water (Mekonnen and Hoekstra, 2011; Hoekstra *et al.*, 2012).

Most of the water that is consumed for coffee production is rain water, or green water. However, after the harvesting of the berries, there are two production processes: a dry and a wet one. In the wet production process, the grey and the blue water footprint of coffee production increases significantly (Chapagain and Hoekstra, 2007). It is visible that in areas where the green water supply is smaller, blue water consumption increases significantly. In areas with a lower water productivity, the result of less precipitation is that ground and surface water becomes necessary for production. In the largest part of the cases, groundwater aquifers are already being overexploited by humans, and thus it is necessary to find ways in producing for which the blue water footprint is lower (Mekonnen and Hoekstra, 2011; Gleeson *et al.*, 2012). The blue water footprint might be decreased by investing in new technology in for example storing green water, or using smart methods in irrigation (Hoekstra and Chapagain, 2007). The same article suggests to shift production processes from areas where water scarcity is a major problem to areas where this problem is less prominent. Economic welfare and water consumption are related: water consumption tends to increase with an increasing economic welfare. An increase of demand for goods and thus an increase of virtual water flows is a cause for this (Hoekstra and Chapagain, 2007).

A virtual water flow emerges when demand for certain goods in one part of the world influences the water consumption in another part of the world. It turns out that as a result of the globalization of trade, the 'real' water flows in a region are often dependent on the demand for goods somewhere else in the world (Chapagain and Hoekstra, 2008; Carr *et al.*, 2013). A concept closely related to this is the virtual water content that is described by Chapagain and Hoekstra (2007). The virtual water content seems to be more or less the same as the water footprint of a product, but it looks into the different phases of the production process. It thus

indicates the amount of water necessary per unit of the good in a certain phase of the production process.

As mentioned before, the water footprint is impacted by economic growth, but also by population growth, production/trade patterns, consumption patterns and technological development (Ercin and Hoekstra, 2014). The availability of the same water is also determined for a large part by human factors. Climatic factors of course play an important role as well, but climate change is amplified by humans (Steinfeld *et al.*, 2020). Contrary to the positive relation between economic welfare and water consumption, is the relation between economic welfare and the negative effects of climate change. The largest effects of climate change are often found in less wealthy countries. Water related problems belong to this category: water security problems often tend to impact both ecological and economic activities at the same time. The most vulnerable areas are the areas that have fewer economic means to invest in a higher water security, and wealthy countries can get away with symptom treatments regarding water security. This causes that existing problems aren't solved fundamentally (Vörösmarty *et al.*, 2010).

Not only water is one of the climatic stressors that has a high influence on the production of coffee, temperature also is of high influence (Gay *et al.*, 2006). The coffee plants itself are dependent on the height of the temperature, and fluctuations in temperature, but also the different coffee pests depend on the temperature. For example the most frequent occurring pest for coffee, the coffee berry borer (*Hypothenemus hampei*), appears to do well in warmer climates. When this pest will be able to increase its geographical spread as a result of a warming climate, mainly the production of the Arabica coffee (*coffea arabica* or *c. arabica*) will be heavily impacted (Jaramillo *et al.*, 2011).

In different parts of the world, different methods for coffee cultivation are found. In regions such as Brazil, the largest parts of the coffee plantations are in full sunlight. Advantages of this are a higher production per plant, and there are more possibilities for mechanization. The downside of this is a higher risk for hydric stress, heat stress, and a higher vulnerability to for example a high variability in temperature. In other parts of the world, such as Central America and in Indonesia, there are shaded plantations, often in the form of agroforest systems (Vieira, 2008; Siles *et al.*, 2010). An agroforest system is a method for agriculture in which coffee is grown under trees. Trees provide for shade, and can function as a temperature buffer for coffee, so heat stress will be less problematic, and the evaporation from the coffee plants will be lower. The water consumption of the agroforest systems is however higher than in monoculture systems (Lin, 2007; Siles *et al.*, 2010)

Agroforestry systems have various advantages for the production and growth of coffee (Siles *et al.*, 2010). For example, as the trees provide shade for the coffee, some sort of a temperature buffer is created, and this reduces the stress caused by large temperature variations. This is only useful when there is an urgent need for shade, such as in locations with a warm and dry climate and the different coffee species would experience different effects. For example, Arabica coffee is more vulnerable to higher temperatures, where Robusta coffee will suffer more from a higher variability in temperatures (Beer *et al.*, 1998; Bunn *et al.*, 2015). The average life span of a coffee plantation is around 30 years, and thus, most coffee plantations will suffer from climate change. In the near future, the suitability for coffee production of areas such as Mexico and the Southeast of Africa might decrease significantly (Bunn *et al.*, 2015).

The water footprint of a single catchment area is determined by many factors. These factors are indicated in the Water Footprint Assessment Manual that was developed by Hoekstra *et al.* (2012). In Figure 1, figure 3.1 of the Water Footprint Assessment Manual is simplified and adjusted to the needs of this research. This conceptual model serves as a basis for calculating the water footprint. The factors indicated in the model should be taken into account when a

model is developed that determines the change in water footprint of coffee production. The sum of the water footprints of every single step in the production process is the total water footprint of the production process. The sum of the water footprints of all production processes in an area is the water footprint of a geographical delineated area (Hoekstra *et al.*, 2012). The water footprint of a product is expressed as water volume per unit of the product. As mass is best applicable for the case of coffee, the water footprint will be given as water volume per unit of mass. In this research, the specific water footprint of coffee for different areas is modelled.

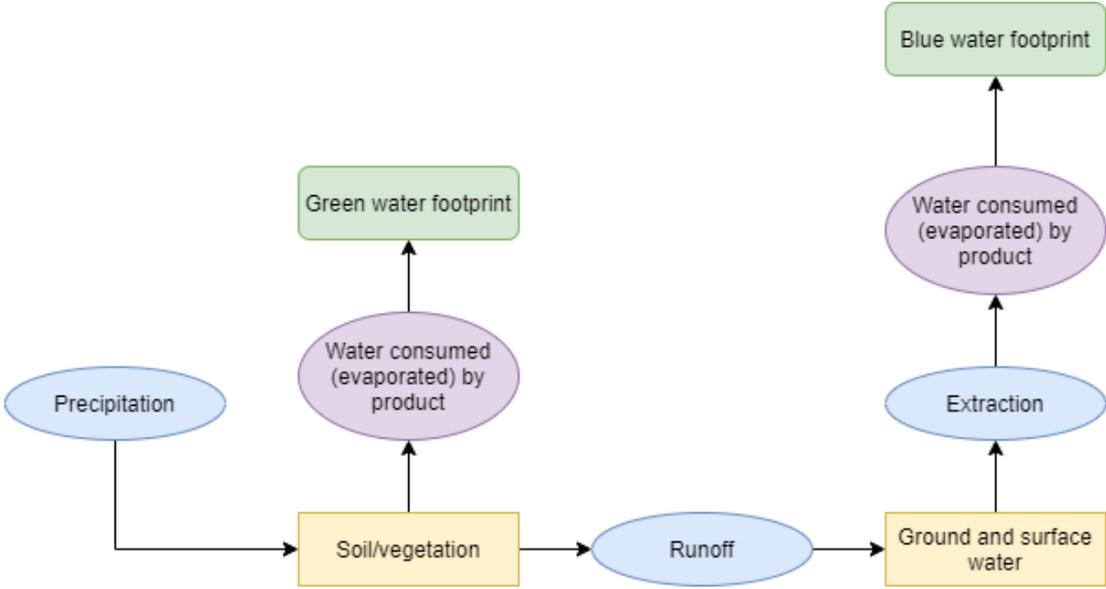


Figure 1 – Conceptual model

4. Methodology

In the research, there is chosen for a global, quantitative approach. An analysis of secondary data is executed. Most variables used in the research are ratio variables, which enabled for many numerical and spatial analyses. The data on de coffee production provided for a basis when starting the spatial analyses. Spatial locations can be seen as numerical values: every point on the earth has been assigned a coordinate. Thus, the coffee producing locations served as a framework to start the rest of the analyses.

To answer sub-question 1, “*What are current locations for coffee production?*” the data provided by the International Coffee Organization (ICO) gives an overview of the current coffee producing countries. The ICO provides data on coffee production, and this data is openly accessible. The dataset begins in the year 1990. For the research, mainly recent coffee production is necessary. The dataset only contains data on all coffee exporting countries, and will thus not include all coffee producing countries. However, it contains data on most countries, and these will be the countries that produce most coffee. Therefore, this dataset is deemed sufficient to provide for a rough picture on where coffee is being produced. For the research, it is expected to cover enough of the current coffee producing areas to be able to do analyses. The coffee producing countries in itself are nominal variables, and those served as a basis for spatial analyses, as are made before in courses such as Geographical Information Systems, and Environment and Engineering. By using GIS-software, in this case a combination of ArcGIS Pro and QGIS, the coffee producing countries are visualized on a map. This was as a basis to be able to use the results of research questions 2, 3, and 4 and translate this to a useful whole.

For sub-question 2, several aspects are taken into account. To answer the question in which parts of the world coffee cultivation is already losing its sustainability, a spatial analysis was done by the use of QGIS. The different components precipitation, temperature, evaporation and frost probability were used to execute a raster calculation which shows the suitability of the current coffee producing areas. The regional data on temperature and precipitation projections are provided by the IPCC. The different climate scenarios that they have provided, are available for use as ArcGIS Feature Services through the portal of ArcGIS online. Thus, the shapefiles are provided by the IPCC, via ESRI. As the IPCC is the authority regarding climate change, and ESRI is one of the main authorities regarding Geographical Information Systems, the data provided is judged to be of a trustworthy quality. There is a chance that the data has lost some of its quality in the process of converting the IPCC data to shapefiles, but this would happen as well when executing this task as part of the research. As there is limited time, there is chosen to use this data. The PCR-GLOBWB model that is developed by the University of Utrecht is perfectly suitable to provide for maps regarding evaporation. The raster data is provided on a level of detail of 30x30 arcmin (Sutanudjaja *et al.*, 2018). See Appendix 4 for the configuration file that was used for running this model.

As a more often used method is to use the model by Sutanudjaja *et al.* (2018), and it is an internationally acknowledged model, it is argued that this model, and the data provided together with the model, are suitable for this research. To finally answer the question, the agrometeorological parameters mentioned in Table 1 are found to be necessary for coffee production, and thus a division can be made based on these parameters (Zullo *et al.*, 2011).

For all spatial analyses, raster data was used. This data was all converted to be the same raster format. The files are in a GeoTIFF format, and the all the raster files have, or are converted to a raster with, the following characteristics:

- CRS = EPSG:4326 – WGS84
- Range = X [-180,180], Y [-90,90]
- Columns: 720
- Rows = 360
- Cell size X = 0,5 Cell size Y = 0,5

Table 1 - Agrometeorological parameters

Climatic risk	Agrometeorological parameter		
	Annual mean temperature	Annual water deficit	Frost probability
Low risks (no restrictions)	$\geq 18 \text{ and } \leq 22$	$\geq 0 \text{ and } \leq 100 \text{ mm}$	$\leq 25\%$
Risk of high temperatures	$\geq 22 \text{ and } \leq 23$	$\geq 0 \text{ and } \leq 100 \text{ mm}$	$\leq 25\%$
Risk of frosts	$\geq 18 \text{ and } \leq 22$	$\geq 0 \text{ and } \leq 100 \text{ mm}$	$> 25\%$
High risks	$\leq 18 \text{ and } \geq 23$	$\geq 150 \text{ mm}$	$> 25\%$

To answer sub-question 3, ‘what are climate projections for the current coffee producing areas?’ the different projections as provided by the IPCC were used. These are accessible as ESRI Feature services through the ArcGIS Online portal. To use this data for further analysis, it should be in the same format as the climatic data calculated by the PCR-GLOBWB model. Therefore, there is chosen for the earlier mentioned characteristics for the datasets. As the PCR-GLOBWB model provides for mesh layers on a resolution of 30x30 arcmin, the resolution

of the raster layers concerning temperature and precipitation provided by the WorldClim data should be of the same resolution of 30x30 arcmin (Fick and Hijmans, 2017). Therefore, those datasets that were not in this resolution yet, were converted to another.

By the combination of the data of sub-questions 2 and 3, sub-question 4 could be answered: “Which areas are likely to experience a decline in the sustainability of coffee production in the (near) future?” By using the raster calculation tools in QGIS, several scripts were written to calculate which areas will be losing their sustainability in for coffee production in the (near) future (Appendix 1-3). The different climate scenarios provided by the IPCC all give different outcomes, and thus as a final step, the way in which an area is affected by the climate change was calculated per climate scenario.

5. Results

The results for the different research questions are given and described in this chapter. Per sub-question, one sub-chapter is given, and at the end of the chapter, the results for the main research question are provided. For sub-question 3 and 4, a regional approach is used to structure the results section: it makes more sense to bundle the results per area, than per sub-question here.

5.1 Locations for coffee cultivation

Sub-question 1, “*What are current locations for coffee cultivation?*”, is answered by an analysis of the data provided by the International Coffee Organization (ICO). At this moment, there are according to the data provided by the ICO 56 countries that export and produce coffee. Of these countries, the largest part produces both the Arabica and the Robusta berry Figure 2 **Fout! Verwijzingsbron niet gevonden..** Of the total coffee consumption, about 70% is Arabica coffee (Vieira, 2008; Magrath and Ghazoul, 2015). The Arabica berry has a higher market value, and grows better in milder climates, such as found on higher altitudes. The Robusta however, is better weaponed against hydric deficit, but it is more susceptible to for example the earlier mentioned berry borer. **Fout! Verwijzingsbron niet gevonden.Fout! Verwijzingsbron niet gevonden.** gives an overview of the coffee producing and exporting countries. It is visible that coffee production mainly takes place in tropical areas around the equator (Vieira, 2008). This is consistent with the fact that for coffee production, an ideal annual average temperature lies between 18 and 22 °C (Zullo *et al.*, 2011).

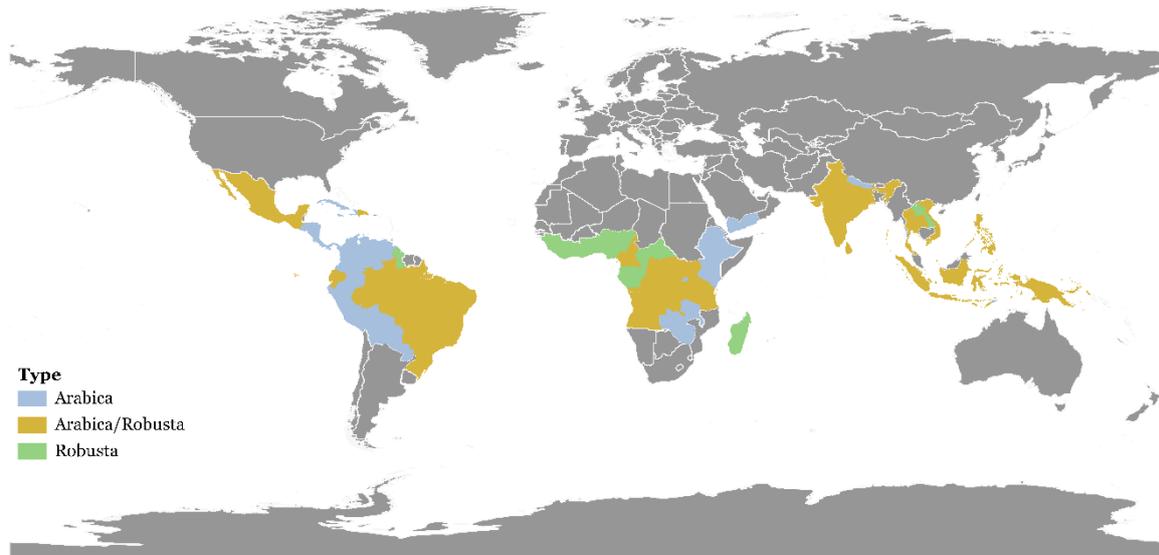


Figure 2 - Coffee producing countries

The approach to for example shade management varies between the different coffee producing regions: in Brazil for example, coffee plantations are in full sun, whereas in Central America and Asia the largest part of the coffee plantations are shaded. Both have advantages and disadvantages: the plantations in full sunlight have a higher productivity per plant/area, but these plantations are more vulnerable to hydric stress and pests such as the berry borer. The shaded plantations have a lower productivity, but are less vulnerable to pests and hydric stress. Also, there is less environmental disturbance, and the need for advanced technology is smaller. Agroforestry systems, or shaded systems seems to be more able to prevent for extremes in the microclimates that occur in coffee plantations (Beer *et al.*, 1998; Moguel and Toledo, 1999; Lin, 2007; Vieira, 2008; Aerts *et al.*, 2017).

5.2 Suitability current locations for coffee cultivation

To find an answer to the second sub-question, “Which current locations for coffee production are not suitable for sustainable coffee production?”, it is necessary to know that there are three main factors contributing to the suitability of a location for coffee cultivation. These are temperature, frost probability, and the availability of water. These factors are called agrometeorological parameters. For the production of Arabica coffee, the ideal annual mean temperature is found between 18°C and 22°C. For crop production, an annual mean temperature of 23°C can be seen as the maximum, but in this case, yields will be less. The frost probability should be below 25%. The annual water deficit should be less than 100 mm (Zullo *et al.*, 2011). When the annual evapotranspiration exceeds the annual rainfall, blue water will need to be used for coffee production. In this research, there is a main focus on the temperature and the availability of water. As visible in Figure 4, 5 and 6, of the areas in which coffee is cultivated, only small parts score sufficient on both temperature and the availability of water. The parts of the maps that are coloured green, are regions in which the cultivation of coffee can be seen as sustainable. The yellow parts indicate a temperature which is on average slightly too high, but not too high for the coffee cultivation. The orange parts score sufficient regarding temperature, but in these areas, there are issues concerning water consumption: where evapotranspiration exceeds numbers of precipitation, blue water is needed for agriculture. Figure 3 shows the legend for all suitability maps.

Legend Suitability

- Temperature 18-22 °C, Water deficit < 100 mm
- Temperature 18-22 °C, Water deficit > 100 mm
- Temperature 22-23 °C, Water deficit < 100 mm

Figure 3 - Legend Suitability coffee cultivation

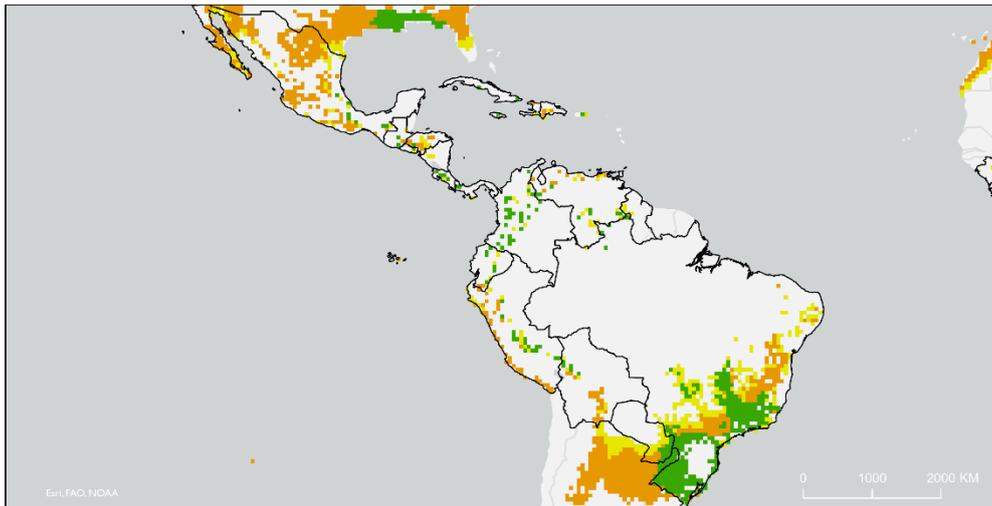


Figure 4 - Suitability for coffee cultivation in the Americas (2020)

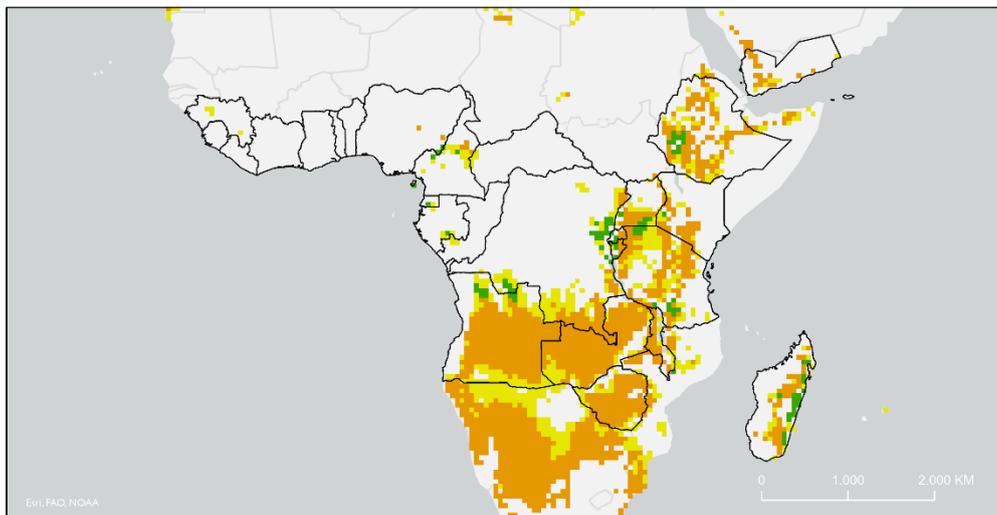


Figure 5 - Suitability for coffee cultivation in Africa (2020)

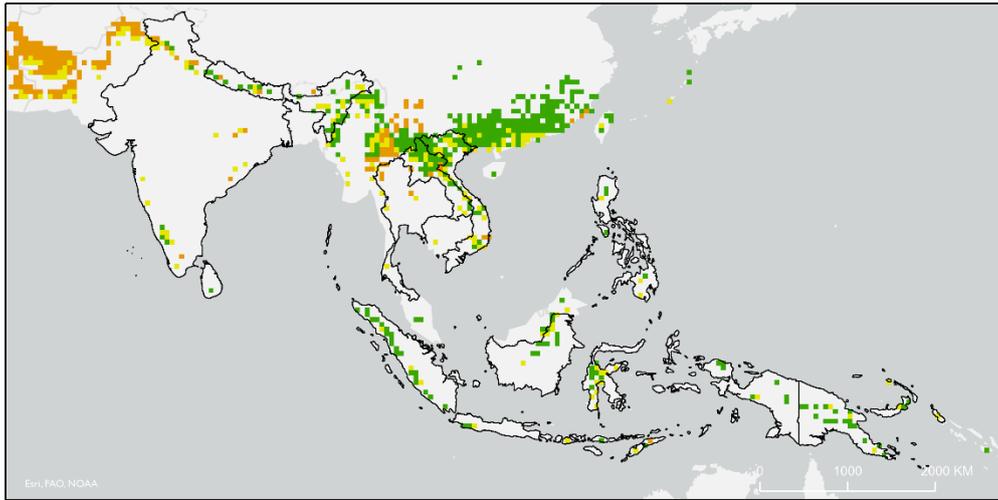


Figure 6 - Suitability for coffee cultivation in South-East Asia (2020)

5.3 Climate projections and future sustainability

For the answer on sub-question 3, “*what are climate projections for the current coffee-producing areas?*” the different climate projections as provided by the IPCC are used. The different climate projections by the IPCC are found as ArcGIS feature services, provided by ESRI. The different scenarios that are used for the analysis are RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The scenarios contain data on both temperature and precipitation. This data is used for answering sub-question 4: “*Which areas are likely to experience a decline in the sustainability of coffee production in the (near) future?*” In the next chapter, there is made a subdivision per area and per climate projection. A short discussion will follow on temperature and precipitation, and this is followed by a discussion on the effects on the sustainability of coffee production. The legends on all temperature and precipitation maps are given below in Figure 7 and 8.

Change in precipitation in mm

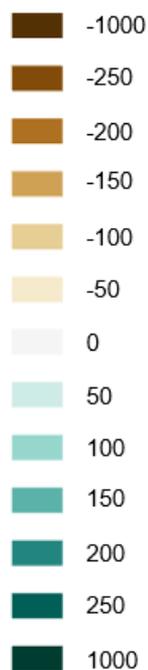


Figure 7 - Legend precipitation projections

Minimal temperature rise in °C

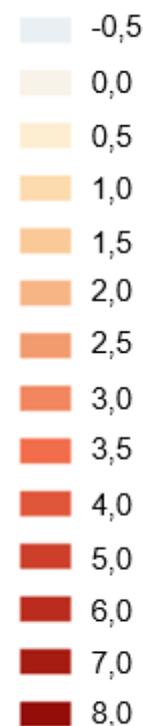


Figure 8 - Legend temperature projections

5.3.1 The Americas

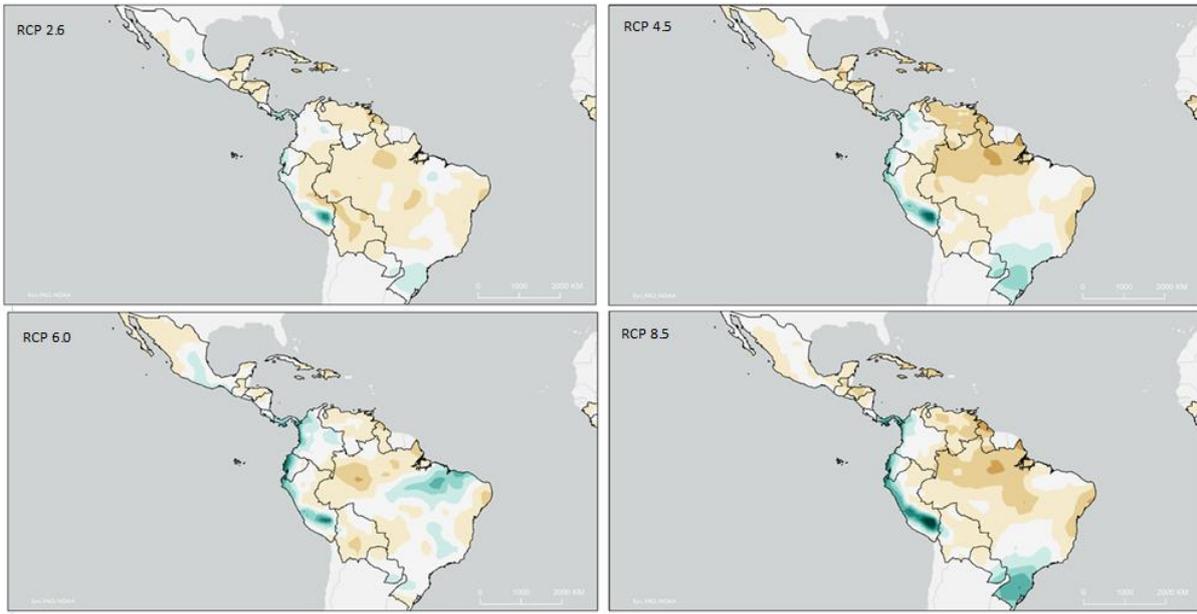


Figure 9 - Precipitation projections for the Americas

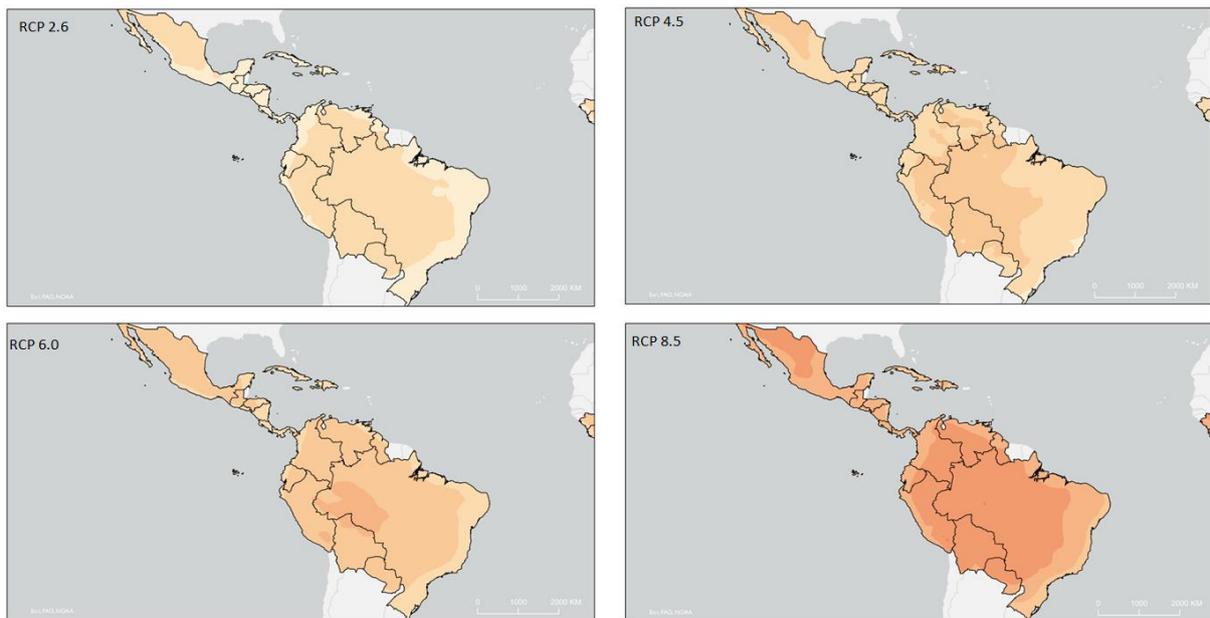


Figure 10 - Temperature projections for the Americas

RCP 2.6

When looking at climate scenario RCP2.6, different elements are visible. One of these is that there will be a small increase in rainfall in the south of Brazil and along the west coast of South-America (Figure 9). Large parts of Mexico and Brazil will experience no difference, or a decrease in precipitation. Next to this, the whole of this area will see a slight increase in temperature, as visible in Figure 10.

The effects of the climate projections on the sustainability of coffee cultivation for the Americas are visualized in Figure 11. The first thing is that there seems to be a decrease in areas that have the highest score concerning sustainability in the Americas. Where an increase in rainfall

might suggest that the sustainability of coffee production in these areas would increase, there first seems to be a decrease. Mainly in the South-Eastern part of Brazil, and the west-coast, there is a large decrease in suitable areas visible. In the north of Mexico, there is an increase visible for areas that have a sufficient temperature for the coffee crop to be cultivated.

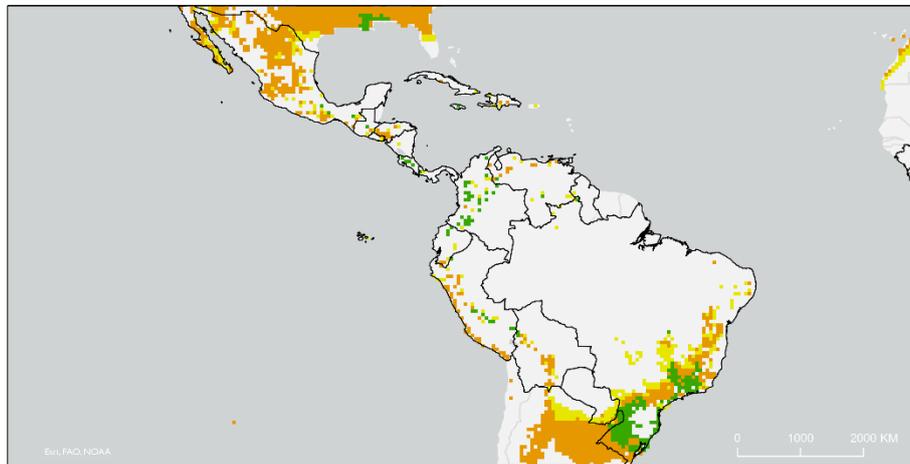


Figure 11 - Sustainability coffee cultivation RCP 2.6 - The Americas

RCP 4.5

Figure 9 gives a clear picture of the ongoing processes in the Americas: in the south of Brazil there is an increase in precipitation. In the other parts of Brazil, and in Mexico, there is a clear decrease in precipitation. Also along the west coast of South-America, a strong increase in precipitation is projected. Concerning temperature, it is clearly visible that there is an increasing temperature from the centre of South Africa towards the coasts. Along the east coast, this increase seems to be the smallest (Figure 10 **Fout! Verwijzingsbron niet gevonden.**). It is visible that in the south of Brazil, there is an increase in area that is suitable for sustainable coffee production. The areas that are suitable in the north of the area are decreasing (Figure 12).

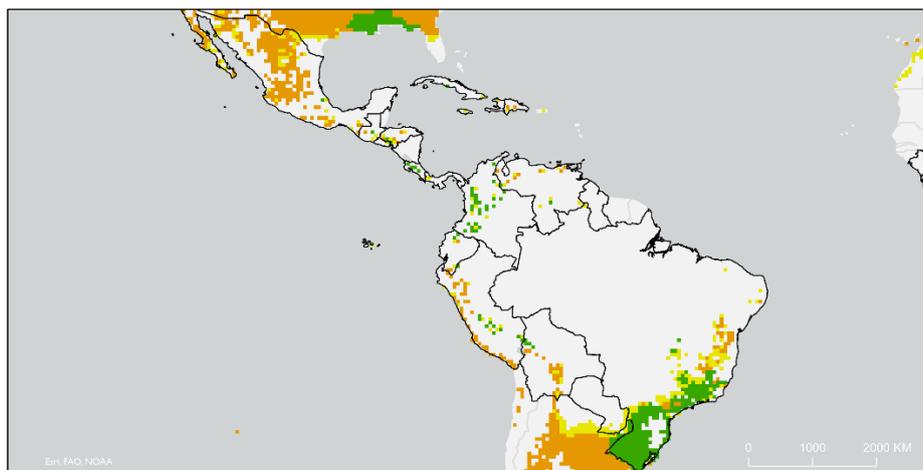


Figure 12 - Sustainability coffee cultivation RCP 4.5 - The Americas

RCP 6.0

In climate scenario RCP 6.0, it is still clearly visible that the area in which coffee can be cultivated in a sustainable manner increases in the south of Brazil (Figure 13). That this process doesn't occur along the west coast of South America might be caused by the fact that here, there is not only an increase of precipitation, but also a stronger increase of temperature than along the east coast (Figure 9, Figure 10). A difference compared towards RCP 4.5 is that in RCP 6.0 the increase in precipitation is mostly visible in the north east of Brazil, instead of the south.

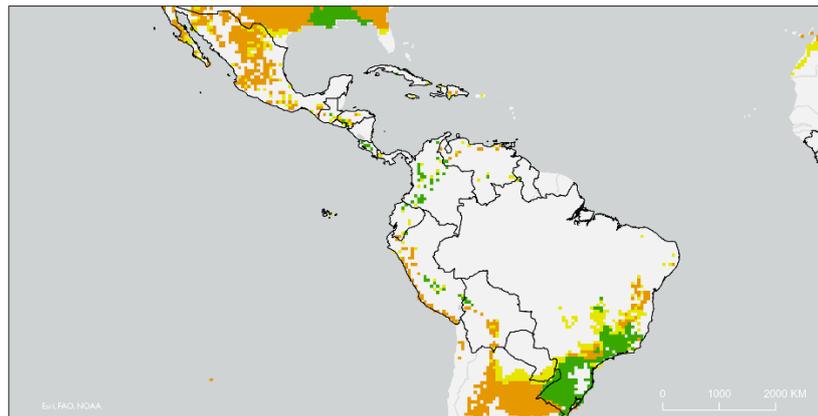


Figure 13 - Sustainability coffee cultivation RCP 6.0 - The Americas

RCP 8.5

For climate scenario RCP 8.5, there is a strong increase in temperature projected (Figure 10) **Fout! Verwijzingsbron niet gevonden..** Next to this, large parts of Brazil, Mexico and Venezuela will experience a significant decrease in rainfall (Figure 9). This causes that there are areas that were suitable for coffee cultivation, tend to become less suitable. The total area that is suitable for coffee production will decrease, as visible in Figure 14.

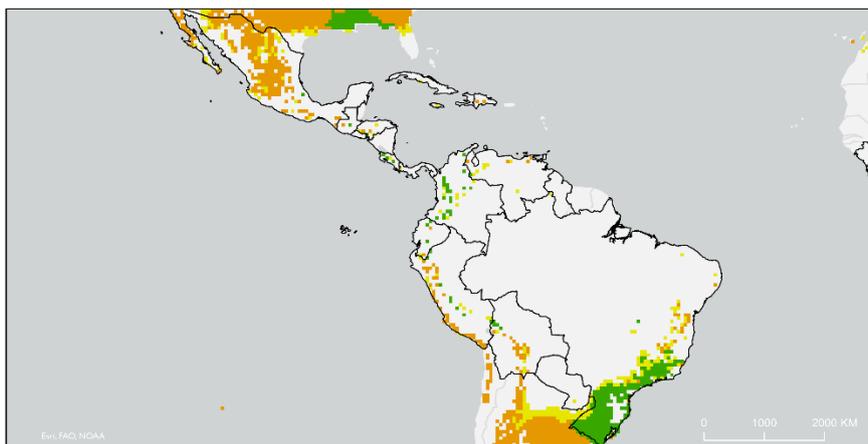


Figure 14 - Sustainability coffee cultivation RCP 8.5

5.3.2 Africa

The climate projections for Africa cause that there is little variation in the outcomes of the calculations. Therefore, the results per climate projection are not discussed separately. The different climate projections on precipitation and temperature are visualized in Figure 15 and 16 respectively.

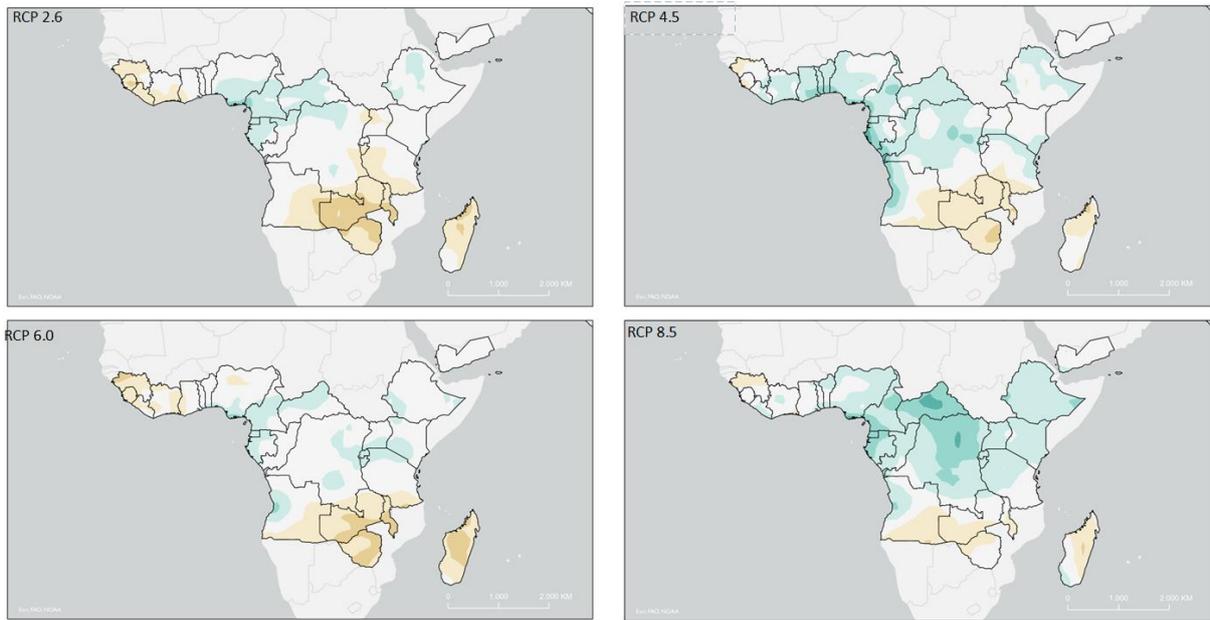


Figure 15 - Precipitation projections for Africa

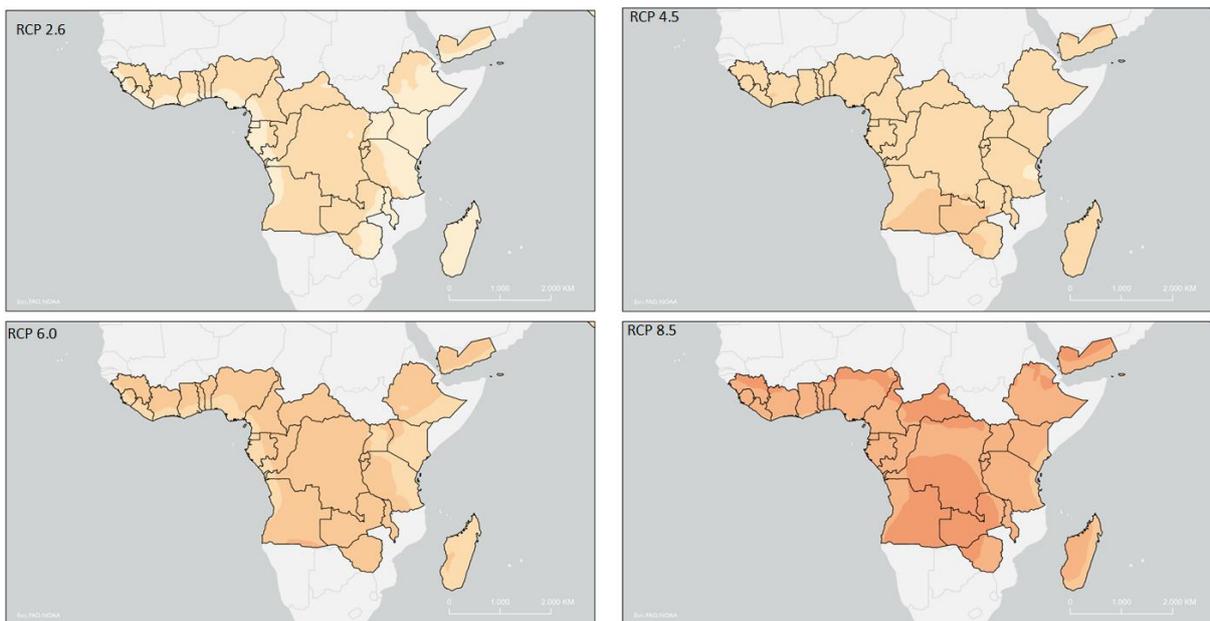


Figure 16 - Temperature projections for Africa

What follows, is Figure 17 that indicates the sustainability of coffee production in Africa when following climate scenario RCP 2.6. In this area, mainly in south-eastern Africa, it is already clearly visible what the influence of increasing temperatures (Figure 16), and increasing drought is on the suitability of this area for coffee production (Figure 15). Where at the starting point in 2020 there are areas that are noted as areas in which coffee can be

cultivated in a sustainable manner, these areas rapidly decrease as a result of a changing climate.

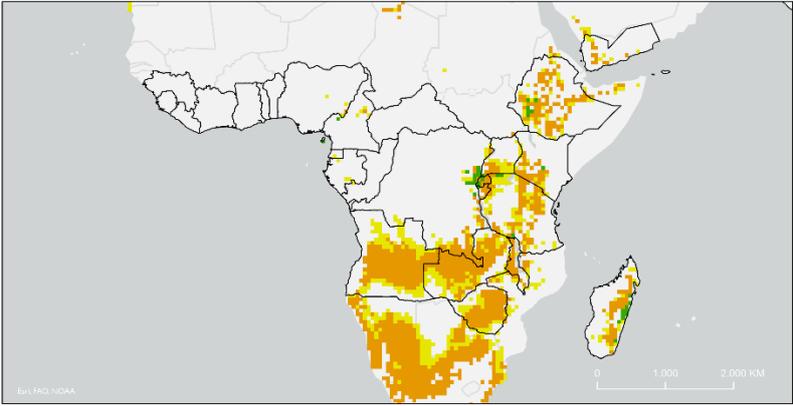


Figure 17 - Sustainability coffee cultivation RCP 2.6 - Africa

Compared to RCP 2.6, RCP 4.5 brings little surprising elements. The largest parts of the area will experience more drought (Figure 15), higher temperatures (Figure 15) and less area that might be suitable for sustainable coffee cultivation (Figure 18).

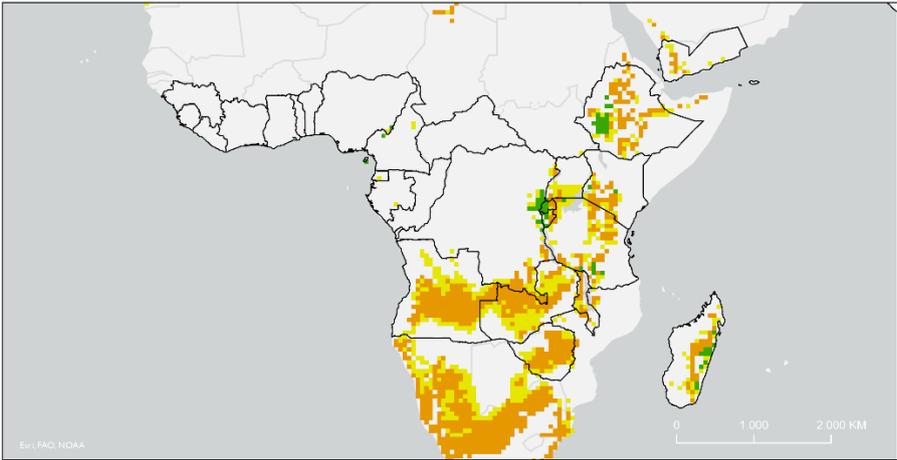


Figure 18 - Sustainability coffee cultivation RCP 4.5 - Africa

When looking at the other climate scenarios and its possible outcomes, one clear trend is visible: temperature increases, precipitation decreases, and the area that is suitable for sustainable coffee cultivation decreases dramatically. This is visualized in Figure 19 and Figure 20 below.

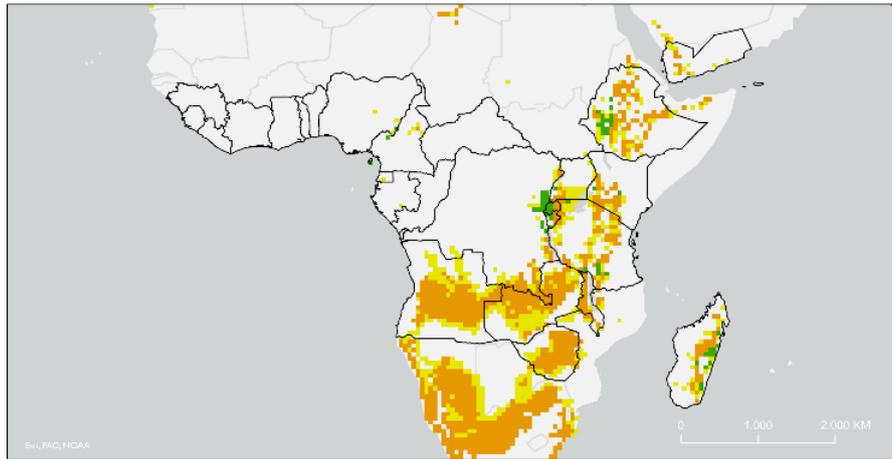


Figure 19 -Sustainability coffee cultivation RCP 6.0 - Africa

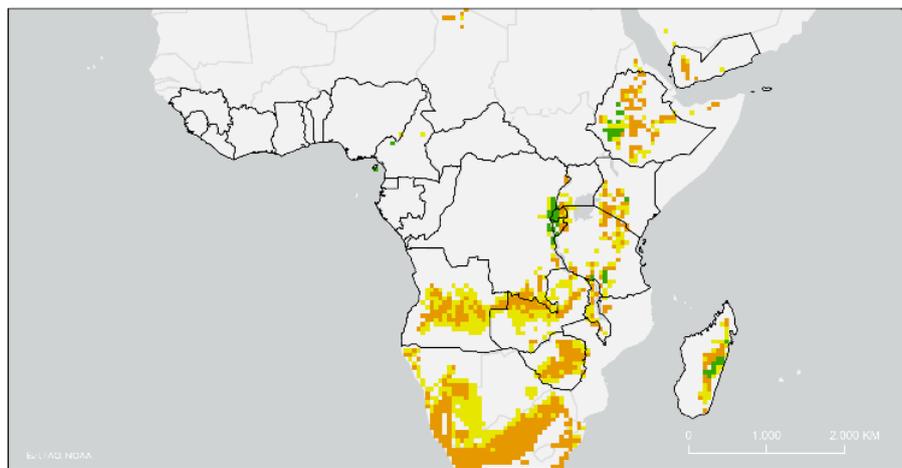


Figure 20 - Sustainability coffee cultivation RCP 8.5 - Africa

5.3.3 South-East Asia

South-East Asia shows a slightly different pattern than Africa and the Americas. Again, temperature increases in the whole of the area for all climate scenarios (Figure 22). However, in this area, there are large differences visible in terms of precipitation. In nearly the whole region, the amount of precipitation will increase as a result of climate change. The only exceptions for this are found in the north of India, and Java. Only Java shows a significant decrease in precipitation (Figure 21). 2

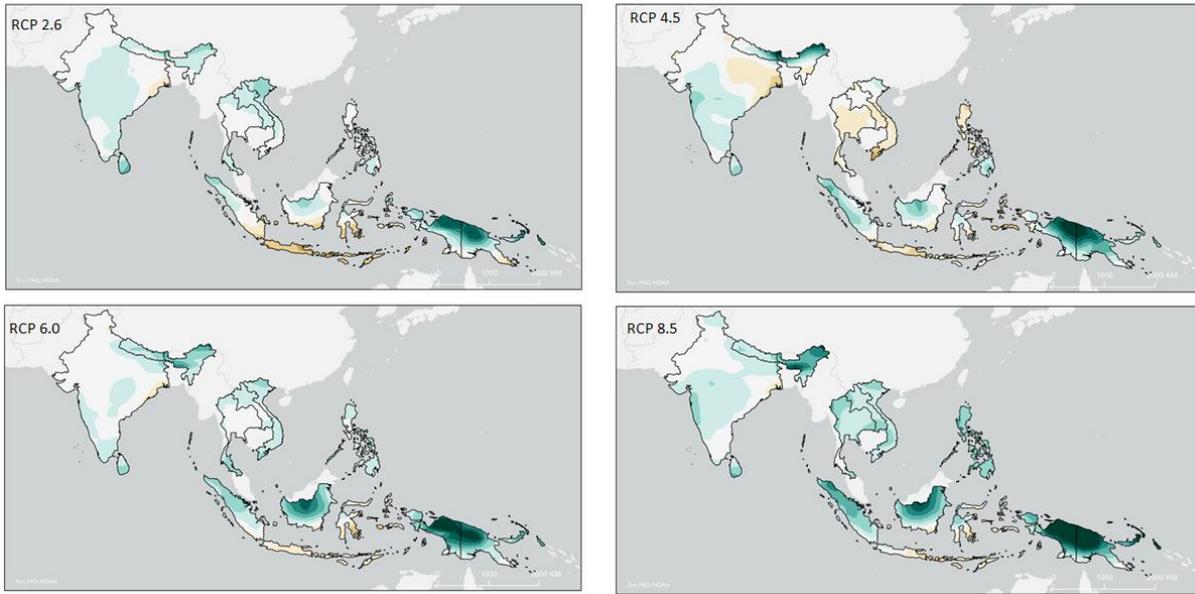


Figure 21 - Precipitation projections for South-East Asia

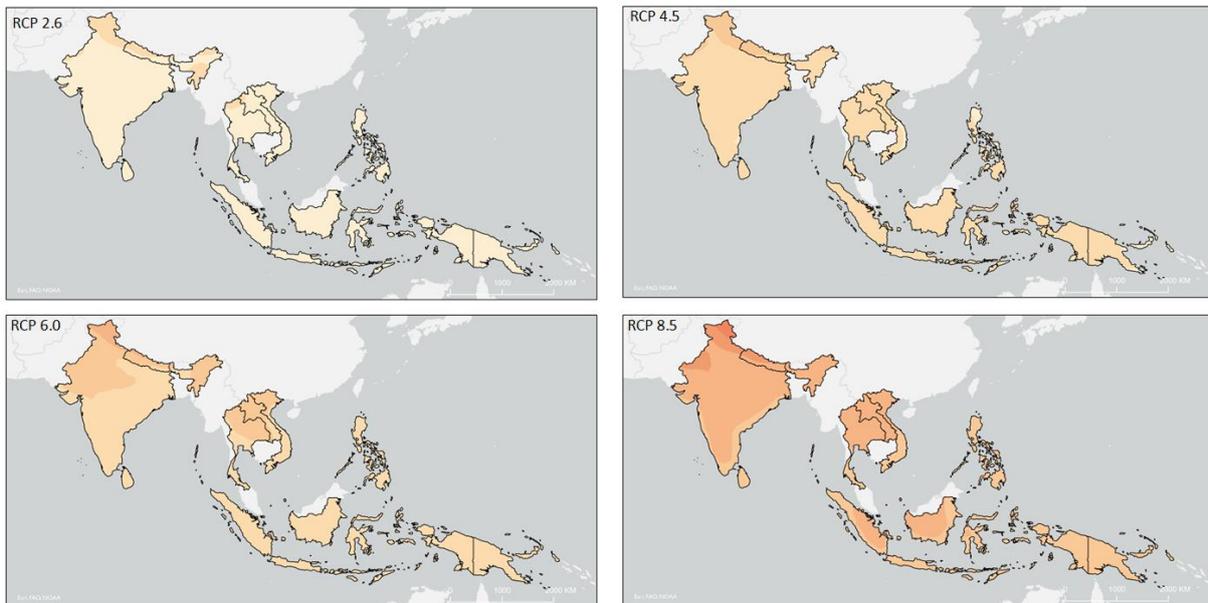


Figure 22 - Temperature projections for South-East Asia

The initial change in surface that is suitable for sustainable coffee production seems to decrease when following climate projection RCP 2.6 (Figure 23) . However, when looking at the other climate scenarios 4.5 to 8.5, another pattern is visible (Figure 24-26). The area that would be suitable for sustainable coffee production is found to be increasing. This area is however shifting to the north. The result is that the areas that are suitable for sustainable coffee cultivation will be moving outside of the current coffee producing countries.

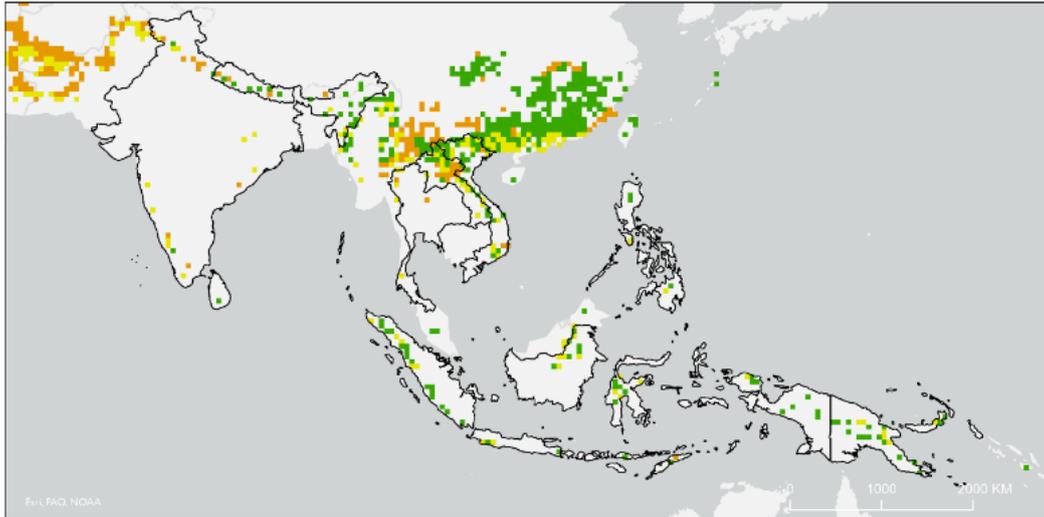


Figure 23 - Sustainability coffee cultivation RCP 2.6 - South-East Asia

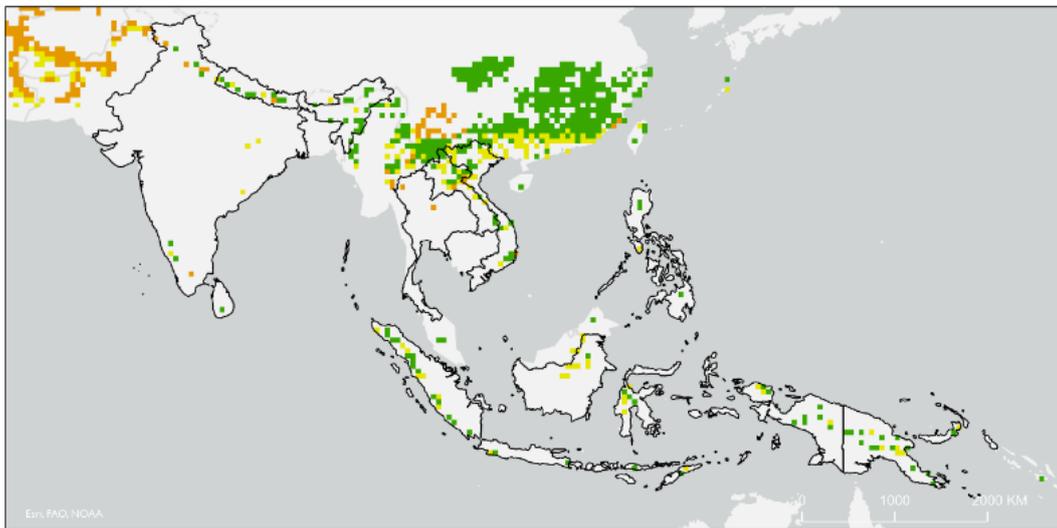


Figure 24 - Sustainability coffee cultivation RCP 4.5 - South-East Asia

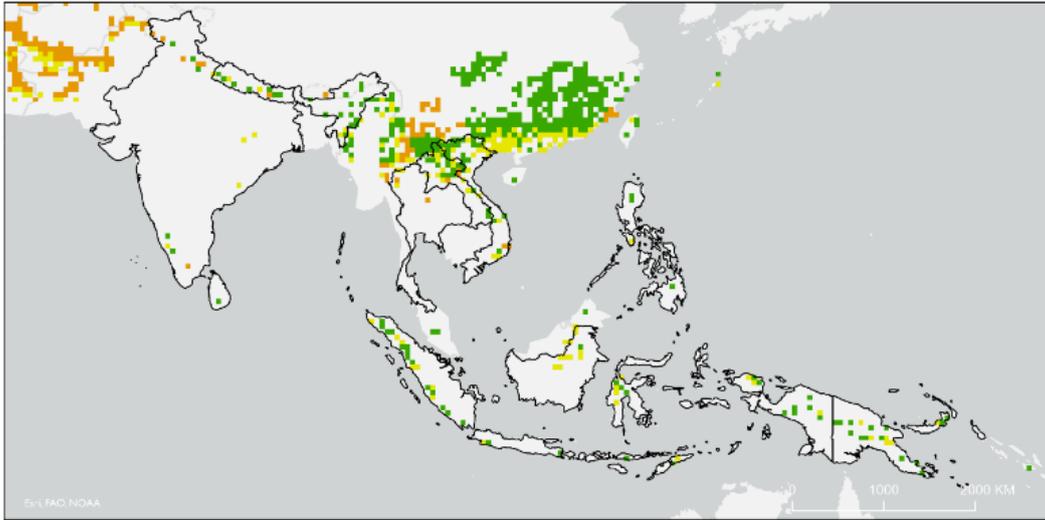


Figure 25 - Sustainability coffee cultivation RCP 6.0 - South-East Asia

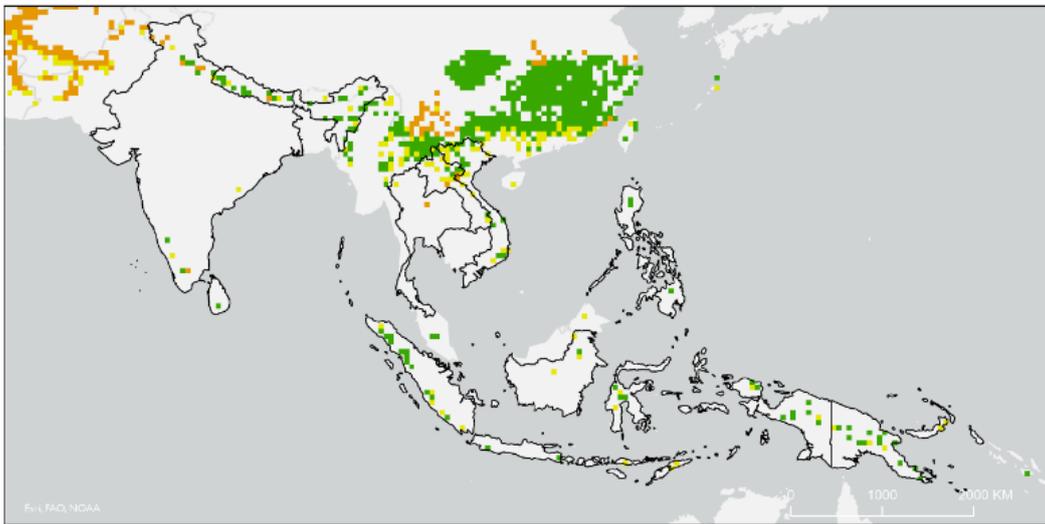


Figure 26 - Sustainability coffee cultivation RCP 8.5 - South-East Asia

6. Conclusions

To answer the main research question, “*How does climate change influence the water footprint of coffee production and what are the implications for future coffee production?*” the different sub-questions all have been answered. The most obvious conclusion that can be drawn from this research is that the topic of sustainable coffee production will be one that becomes more and more relevant in the coming years. As was discovered during the analyses, clear differences are found in between the regions in which at this moment coffee is cultivated. Compared to the amount of countries that produce and export coffee, the area that is suitable for sustainable coffee production is very small, as results from sub-questions 1 and 2. This area is very likely to decrease in the near future, as for all climate scenarios, a significant decrease of this area is also visible. Few areas will experience an increase for the suitability of sustainable coffee production, and these areas will most probably be moving outside of the current areas of where coffee cultivation takes place.

7. Discussion

The research into the sustainability of coffee cultivation has its downsides and weak points. To start off, different problems occurred when working with the PCR-GLOBWB Model, which caused that there was a need to search for a different approach on the spatial analysis. The different datasets all were of different formats, and thus needed to be converted to the same format. A loss of data is here unavoidable. Furthermore, there are many more variables determining the suitability of an area than only temperature and water availability. However, due to the scope of this research, there is chosen to make an analysis based on these criteria. A difference that is found when comparing this research to for example that of Bunn *et al.* (2015) is the fact that the area that is ideal for coffee production is larger in the research of Bunn *et al.* (2015). This might be caused by the fact that the temperature range that is used by Bunn *et al.* (2015) differs from the temperature range used in this research. The research by Bunn *et al.* (2015) uses slightly different criteria, as it for example uses more climatic variables. Nevertheless, a comparable trend is visible. This is in accordance with the more general trend in literature regarding coffee cultivation in a changing climate. The general trend in literature regarding the impact of climate change on coffee cultivation is that a large impact is expected for the coffee cultivation (Gay *et al.*, 2006; Schroth *et al.*, 2009; Jaramillo *et al.*, 2011; Waha *et al.*, 2013; Craparo *et al.*, 2015). Those involved in the process of coffee cultivation, will most likely suffer a lot from the expected climate change. This will not only be on the scale of one plantation, but also on the scale of a country, and thus the effects will be visible on a global scale (Craparo *et al.*, 2015).

The lifespan of a coffee plantation is about 30 years, and major geographical shifts regarding the sustainability of locations for coffee cultivation are expected. This is strengthened by the fact that also Bunn *et al.* (2015) find a decreasing area that is suitable for the Arabica coffee, and a shifting area for the Robusta coffee. This will effect in plantation owners losing their plantations as yields go down, or there is too much irrigation needed for the process of cultivation to be economically feasible. There is an urge to investigate what implications are for the different systems for coffee cultivation. Earlier was the distinction between agroforestry and full-sun plantations made. The different systems, combined with different political and economic situations and choices will see different effects of the climate change.

To be able to make a better analysis, and to draw more accurate conclusions, it will be necessary to have a more extensive investigation. In this investigation, there should also be looked into the differences between Arabica and Robusta coffee, and the irrigation needs per plantation or region. Future evapotranspiration should be estimated using more complex models and data. As the water footprint of coffee cultivation is high, it is wise to look into methods which decrease the water footprint of coffee cultivation: it is advised to investigate methods to store green water to be prepared for a fluctuating precipitation pattern. It would be wise to look into smart methods of irrigation, in which less water would be used. When this is successful, the many persons who are dependent on the production and cultivation of coffee would be helped.

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Appendix 1 – Precipitation projections – script

The steps are all executed separately.

```
# precipitation projections

# RCP2.6
prec26 = 'D:\GIS\Bachelor _Project\Raster\prec26.tif'
output = 'D:\GIS\Bachelor_project\Raster\water26.tif'
entries = []

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@1'
ras.layer = prec26
ras.bandNumber = 1
entries.append(ras)

# annual precipitation
bio12 = 'D:\GIS\Bachelor_Project\Data\Rasters\Precipitation.tif'
output2= 'D:\GIS\Bachelor_Project\Data\Rasters\Precipitation2.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@2'
ras.layer = bio12
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@1' + 'ras@2' , output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP4.5
prec45 = 'D:\GIS\Bachelor _Project\Raster\prec45.tif'
output3 = 'D:\GIS\Bachelor_project\Raster\water45.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@3'
ras.layer = prec45
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@2'+ 'ras@3', output3, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP6.0
prec60 = 'D:\GIS\Bachelor _Project\Raster\prec60.tif'
output4 = 'D:\GIS\Bachelor_project\Raster\water60.tif'

ras = QgisRasterCalculatorEntry()
```

```

res.ref = 'ras@4'
ras.layer = prec60
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@2' + 'ras@4', output4, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP8.5
prec85 = 'D:\GIS\Bachelor _Project\Raster\prec85.tif'
output5 = 'D:\GIS\Bachelor_project\Raster\water85.tif'

ras = QgsRasterCalculatorEntry()
res.ref = 'ras@5'
ras.layer = prec85
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@2' + 'ras@5', output5, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

```

Appendix 2 – Temperature Projections – script

The steps are all executed separately.

```
# temperature projections

# RCP2.6
temp26 = 'D:\GIS\Bachelor _Project\Raster\temp26.tif'
output = 'D:\GIS\Bachelor_project\Raster\tottemp26.tif'
entries = []

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@1'
ras.layer = temp26
ras.bandNumber = 1
entries.append(ras)

# annual temperature
bio1 = 'D:\GIS\Bachelor_Project\Data\Rasters\temperature.tif'
output2 = 'D:\GIS\Bachelor_Project\Data\Rasters\temperature2.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@2'
ras.layer = bio1
ras.bandNumber = 1
entries.append(ras)

calc = QgisRasterCalculator('ras@1' + 'ras@2' , output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP4.5
temp45 = 'D:\GIS\Bachelor _Project\Raster\temp45.tif'
output3 = 'D:\GIS\Bachelor_project\Raster\tottemp45.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@3'
ras.layer = temp45
ras.bandNumber = 1
entries.append(ras)

calc = QgisRasterCalculator('ras@2'+ 'ras@3', output3, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP6.0
temp60 = 'D:\GIS\Bachelor _Project\Raster\temp60.tif'
output4 = 'D:\GIS\Bachelor_project\Raster\tottemp60.tif'
```

```

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@4'
ras.layer = tempc60
ras.bandNumber = 1
entries.append(ras)

calc = QgisRasterCalculator('ras@2' + 'ras@4', output4, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP8.5
temp85 = 'D:\GIS\Bachelor _Project\Raster\temp85.tif'
output5 = 'D:\GIS\Bachelor_project\Raster\totemp85.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@5'
ras.layer = temp85
ras.bandNumber = 1
entries.append(ras)

calc = QgisRasterCalculator('ras@2' + 'ras@5', output5, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

```

Appendix 3 – Suitability calculations water – script

The steps are all executed separately.

```
# calculate water deficit

# RCP2.6
water26 = 'D:\GIS\Bachelor _Project\Raster\water26.tif'
output = 'D:\GIS\Bachelor_project\Raster\deficit26.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@1'
ras.layer = water26
ras.bandNumber = 1
entries.append(ras)

#ET0
ET0 = 'D:\GIS\Bachelor_Project\Maps\Temperature_precipitation_analysis\ET0.tif'
'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@2'
ras.layer = ET0
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@1' - 'ras@2' , output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP4.5
water45 = 'D:\GIS\Bachelor_project\Raster\water45.tif'
output = 'D:\GIS\Bachelor_project\Raster\deficit45.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@3'
ras.layer = water45
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@3' - 'ras@2', output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP6.0
prec60 = 'D:\GIS\Bachelor _Project\Raster\water60.tif'
output = 'D:\GIS\Bachelor_project\Raster\deficit60.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@4'
```

```

ras.layer = water60
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@4'-'ras@2', output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

# RCP8.5
prec85 = 'D:\GIS\Bachelor _Project\Raster\water85.tif'
output = 'D:\GIS\Bachelor_project\Raster\deficit85.tif'

ras = QgisRasterCalculatorEntry()
res.ref = 'ras@5'
ras.layer = water85
ras.bandNumber = 1
entries.append(ras)

calc = QgsRasterCalculator('ras@5' - 'ras@2', output, 'GTiff', \
    lyr1.extent(), lyr1.width(), lyr1.height(), entries)
calc.processCalculation()

```

Appendix 4 – Configuration file PCR-GLOBWB model

```
[globalOptions]
```

```
# Please set the pcrglobwb output directory (outputDir) in an absolute path.
# - Please make sure that you have access to it.
#~ outputDir = /scratch/depfg/sutan101/pcrglobwb2_output/30min/
outputDir    = D:\Python\PCR-GLOBWB_model\Output

# Please set the clone map file (cloneMap), which defines the spatial resolution and extent of your study area.
# - Please make sure that the file is stored locally in your computing machine
.
# - The file must be in the pcraster format.
#~ cloneMap = /quanta1/home/hydrowld/data/hydroworld/pcrglobwb2_input_release/version_2019_11_beta/pcrglobwb2_input/global_30min/cloneMaps/clone_global_30min.map
#~ cloneMap = /quanta1/home/hydrowld/data/hydroworld/pcrglobwb2_input_release/version_2019_11_beta/pcrglobwb2_input/global_30min/cloneMaps/RhineMeuse30min.clone.map
cloneMap     = D:\Python\Model_Thesis\30arcm\landmask_global_30min.map

# Set the input directory map in an absolute path. The input forcing and parameter directories and files will be relative to this.
# - The following is an example using files from the opendap server.
inputDir     = https://opendap.4tu.nl/thredds/dodsC/data2/pcrglobwb/version_2019_11_beta/pcrglobwb2_input/
#~ # - The following is an example using input files stored locally in your computing machine.
#~ inputDir = /quanta1/home/hydrowld/data/hydroworld/pcrglobwb2_input_release/version_2019_11_beta/pcrglobwb2_input/

# The area/landmask of interest:
# If None, area/landmask is limited for cells with ldd value.
landmask     = None
#~ landmask = /quanta1/home/hydrowld/data/hydroworld/pcrglobwb2_input_release/version_2019_11_beta/pcrglobwb2_input/global_30min/cloneMaps/RhineMeuse30min.landmask.map

# netcdf attributes for output files:
title        = PCR-GLOBWB 2 output, with human factors (non-natural)
description  = PCR-GLOBWB run with human factors (non-natural) at 30 arcmin resolution

startTime   = 2000-01-01
endTime     = 2010-12-31
# Format: YYYY-MM-DD ; The model runs on daily time step.
```

```

# spinning up options:
maxSpinUpsInYears = 0
minConvForSoilSto = 0.0
minConvForGwatSto = 0.0
minConvForChanSto = 0.0
minConvForTotlSto = 0.0

[meteoOptions]

# Set the forcing temperature and precipitation files (relative to inputDir)
precipitationNC = global_30min/meteo/forcing/daily_precipitation_cru_era-
interim_1979_to_2010.nc
temperatureNC   = global_30min/meteo/forcing/daily_temperature_cru_era-
interim_1979_to_2010.nc

# Method to calculate referencePotETP (reference potential evaporation+transpi-
ration)
# options are "Hamon" and "Input" ; If "Input", the netcdf input file must be
given:
referenceETPotMethod = Input
refETPotFileNC      = global_30min/meteo/forcing/daily_referencePotET_cru_era-
interim_1979_to_2010.nc

[landSurfaceOptions]

debugWaterBalance = True

numberOfUpperSoilLayers = 2

# soil and parameters
# - they are used for all land cover types, unless they are defined in cer-
tain land cover type options
# (e.g. different/various soil types for agriculture areas)
topographyNC      = global_30min/landSurface/topography/topography_parameters_3
0_arcmin_october_2015.nc
soilPropertiesNC  = global_30min/landSurface/soil/soilProperties.nc

includeIrrigation = True

# netcdf time series for historical expansion of irrigation areas (unit: hecta-
res).
# Note: The resolution of this map must be consisten with the resolution of ce-
llArea.
historicalIrrigationArea = global_30min/waterUse/irrigation/irrigated_areas/ir-
rigationArea30ArcMin.nc

```

```

# a pcraster map/value defining irrigation efficiency (dimensionless) - optional
irrigationEfficiency = global_30min/waterUse/irrigation/irrigation_efficiency/efficiency.nc

includeDomesticWaterDemand = True
includeIndustryWaterDemand = True
includeLivestockWaterDemand = True

# domestic, industrial and livestock water demand data (unit must be in m.day-1)
domesticWaterDemandFile = global_30min/waterUse/waterDemand/domestic_water_demand_version_october_2014.nc
industryWaterDemandFile = global_30min/waterUse/waterDemand/industrial_water_demand_version_october_2014.nc
livestockWaterDemandFile = global_30min/waterUse/waterDemand/livestock_water_demand_1960-2012.nc

# desalination water supply (maximum/potential/capacity)
desalinationWater = global_30min/waterUse/desalination/desalination_water_use_version_october_2014.nc

# zone IDs (scale) at which allocations of groundwater and surface water (as well as desalinated water) are performed
allocationSegmentsForGroundSurfaceWater = global_30min/waterUse/abstraction_zones/abstraction_zones_60min_30min.nc

# pcraster maps defining the partitioning of groundwater - surface water source
#
# - predefined surface water - groundwater partitioning for irrigation demand (e.g. based on Siebert, Global Map of Irrigation Areas version 5)
irrigationSurfaceWaterAbstractionFractionData = global_30min/waterUse/source_partitioning/surface_water_fraction_for_irrigation/AEI_SWFRAC.nc
# -- quality map
irrigationSurfaceWaterAbstractionFractionDataQuality = global_30min/waterUse/source_partitioning/surface_water_fraction_for_irrigation/AEI_QUAL.nc
#
# - threshold values defining the preference for surface water source for irrigation purpose
# -
- treshold to maximize surface water irrigation use (cells with irrSurfaceWaterAbstractionFraction above this will prioritize irrigation surface water use)
treshold_to_maximize_irrigation_surface_water = 0.50
# -
- treshold to minimize fossil water withdrawal for irrigation (cells with irrS

```

```

urfaceWaterAbstractionFraction below this have no fossil withdrawal for irriga
tion)
threshold_to_minimize_fossil_groundwater_irrigation      = 0.70
#
# - predefined surface water - groundwater partitioning for non irrigation dem
and (e.g. based on McDonald, 2014)
maximumNonIrrigationSurfaceWaterAbstractionFractionData = global_30min/waterUs
e/source_partitioning/surface_water_fraction_for_non_irrigation/max_city_sw_fr
action.nc

[forestOptions]

name = forest
debugWaterBalance = True

# snow module properties
snowModuleType      = Simple
freezingT           = 0.0
degreeDayFactor     = 0.0025
snowWaterHoldingCap = 0.1
refreezingCoeff     = 0.05

# other parameter values
minTopWaterLayer    = 0.0
minCropKC           = 0.2

cropCoefficientNC   = global_30min/landSurface/landCover/naturalTall/Global_Crop
CoefficientKc-Forest_30min.nc
interceptCapNC      = global_30min/landSurface/landCover/naturalTall/interceptCa
pInputForest366days.nc
coverFractionNC     = global_30min/landSurface/landCover/naturalTall/coverFracti
onInputForest366days.nc

landCoverMapsNC     = global_30min/landSurface/landCover/naturalTall/forestPrope
rties.nc

# initial conditions:
interceptStorIni    = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interceptStor_forest_1999-12-31.nc
snowCoverSWEIni    = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowCoverSWE_forest_1999-12-31.nc
snowFreeWaterIni   = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowFreeWater_forest_1999-12-31.nc
topWaterLayerIni   = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/topWaterLayer_forest_1999-12-31.nc
storUppIni         = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storUpp_forest_1999-12-31.nc

```

```

storLowIni      = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storLow_forest_1999-12-31.nc
interflowIni    = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interflow_forest_1999-12-31.nc

[grasslandOptions]

name = grassland
debugWaterBalance = True

# snow module properties
snowModuleType    = Simple
freezingT         = 0.0
degreeDayFactor   = 0.0025
snowWaterHoldingCap = 0.1
refreezingCoeff   = 0.05

# other parameter values
minTopWaterLayer = 0.0
minCropKC        = 0.2

cropCoefficientNC = global_30min/landSurface/landCover/naturalShort/Global_Cro
pCoefficientKc-Grassland_30min.nc
interceptCapNC   = global_30min/landSurface/landCover/naturalShort/interceptC
apInputGrassland366days.nc
coverFractionNC  = global_30min/landSurface/landCover/naturalShort/coverFract
ionInputGrassland366days.nc

landCoverMapsNC  = global_30min/landSurface/landCover/naturalShort/grasslandPr
operties.nc

# initial conditions:
interceptStorIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interceptStor_grassland_1999-12-31.nc
snowCoverSWEIni  = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowCoverSWE_grassland_1999-12-31.nc
snowFreeWaterIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowFreeWater_grassland_1999-12-31.nc
topWaterLayerIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/topWaterLayer_grassland_1999-12-31.nc
storUppIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storUpp_grassland_1999-12-31.nc
storLowIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storLow_grassland_1999-12-31.nc
interflowIni     = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interflow_grassland_1999-12-31.nc

```

```

[irrPaddyOptions]

name = irrPaddy
debugWaterBalance = True

# snow module properties
snowModuleType      = Simple
freezingT           = 0.0
degreeDayFactor     = 0.0025
snowWaterHoldingCap = 0.1
refreezingCoeff     = 0.05

landCoverMapsNC = global_30min/landSurface/landCover/irrPaddy/paddyProperties
.nc
#
# other parameter values
minTopWaterLayer = 0.05
minCropKC        = 0.2
cropDeplFactor   = 0.2
minInterceptCap  = 0.0002

cropCoefficientNC = global_30min/landSurface/landCover/irrPaddy/Global_CropCoe
fficientKc-IrrPaddy_30min.nc

# initial conditions:
interceptStorIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interceptStor_irrPaddy_1999-12-31.nc
snowCoverSWEIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowCoverSWE_irrPaddy_1999-12-31.nc
snowFreeWaterIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowFreeWater_irrPaddy_1999-12-31.nc
topWaterLayerIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/topWaterLayer_irrPaddy_1999-12-31.nc
storUppIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storUpp_irrPaddy_1999-12-31.nc
storLowIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storLow_irrPaddy_1999-12-31.nc
interflowIni     = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interflow_irrPaddy_1999-12-31.nc

[irrNonPaddyOptions]

name = irrNonPaddy
debugWaterBalance = True

# snow module properties
snowModuleType      = Simple
freezingT           = 0.0

```

```

degreeDayFactor      = 0.0025
snowWaterHoldingCap = 0.1
refreezingCoeff     = 0.05

landCoverMapsNC = global_30min/landSurface/landCover/irrNonPaddy/nonPaddyProp
erties.nc
#
# other parameter values
minTopWaterLayer = 0.0
minCropKC        = 0.2
cropDeplFactor   = 0.5
minInterceptCap  = 0.0002

cropCoefficientNC = global_30min/landSurface/landCover/irrNonPaddy/Global_Crop
CoefficientKc-IrrNonPaddy_30min.nc

# initial conditions:
interceptStorIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interceptStor_irrNonPaddy_1999-12-31.nc
snowCoverSWEIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowCoverSWE_irrNonPaddy_1999-12-31.nc
snowFreeWaterIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/snowFreeWater_irrNonPaddy_1999-12-31.nc
topWaterLayerIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/topWaterLayer_irrNonPaddy_1999-12-31.nc
storUppIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storUpp_irrNonPaddy_1999-12-31.nc
storLowIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/storLow_irrNonPaddy_1999-12-31.nc
interflowIni     = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/interflow_irrNonPaddy_1999-12-31.nc

[groundwaterOptions]

debugWaterBalance = True

groundwaterPropertiesNC = global_30min/groundwater/properties/groundwaterPrope
rties.nc
# The file will containspecificYield (m3.m-3), kSatAquifer (m.day-
1), recessionCoeff (day-1)
#
# - minimum value for groundwater recession coefficient (day-1)
minRecessionCoeff = 1.0e-4

# some options for constraining groundwater abstraction
limitFossilGroundWaterAbstraction = True

```

```

estimateOfRenewableGroundwaterCapacity = 0.0
estimateOfTotalGroundwaterThickness   = global_30min/groundwater/aquifer_thic
kness_estimate/thickness_30min.nc
# minimum and maximum total groundwater thickness
minimumTotalGroundwaterThickness      = 100.
maximumTotalGroundwaterThickness       = None

# annual pumping capacity for each region (unit: billion cubic meter per year)
, should be given in a netcdf file
pumpingCapacityNC = global_30min/waterUse/groundwater_pumping_capacity/regiona
l_abstraction_limit.nc

# initial conditions:
storGroundwaterIni                      = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/storGroundwater_1999-12-31.nc
storGroundwaterFossilIni                = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/storGroundwaterFossil_1999-12-31.nc
#
# additional initial conditions for pumping behaviors
avgNonFossilGroundwaterAllocationLongIni = global_30min/initialConditions/non
-
natural/consistent_run_201903XX/1999/avgNonFossilGroundwaterAllocationLong_199
9-12-31.nc
avgNonFossilGroundwaterAllocationShortIni = global_30min/initialConditions/non
-
natural/consistent_run_201903XX/1999/avgNonFossilGroundwaterAllocationShort_19
99-12-31.nc
avgTotalGroundwaterAbstractionIni        = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/avgTotalGroundwaterAbstraction_1999-12-
31.nc
avgTotalGroundwaterAllocationLongIni     = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/avgTotalGroundwaterAllocationLong_1999-
12-31.nc
avgTotalGroundwaterAllocationShortIni    = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/avgTotalGroundwaterAllocationShort_1999-
12-31.nc
#
# additional initial conditions (needed only for MODFLOW run)
relativeGroundwaterHeadIni              = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/relativeGroundwaterHead_1999-12-31.nc
baseflowIni                              = global_30min/initialConditions/non
-natural/consistent_run_201903XX/1999/baseflow_1999-12-31.nc

# zonal IDs (scale) at which zonal allocation of groundwater is performed
allocationSegmentsForGroundwater = global_30min/waterUse/abstraction_zones/abs
traction_zones_30min_30min.nc

```

```

[routingOptions]

debugWaterBalance = True

# drainage direction map
lddMap          = global_30min/routing/ldd_and_cell_area/lddsound_30min.nc

# cell area (unit: m2)
cellAreaMap     = global_30min/routing/ldd_and_cell_area/cellarea30min.nc

# routing method:
routingMethod   = accuTravelTime
#~ routingMethod = kinematicWave

# manning coefficient
manningsN      = 0.04

# Option for flood plain simulation
dynamicFloodPlain = True

# manning coefficient for floodplain
floodplainManningsN = 0.07

# channel gradient
gradient       = global_30min/routing/channel_properties/channel_gradient.nc

# constant channel depth
constantChannelDepth = global_30min/routing/channel_properties/bankfull_depth.nc

# constant channel width (optional)
constantChannelWidth = global_30min/routing/channel_properties/bankfull_width.nc

# minimum channel width (optional)
minimumChannelWidth = global_30min/routing/channel_properties/bankfull_width.nc

# channel properties for flooding
bankfullCapacity   = None
# - If None, it will be estimated from (bankfull) channel depth (m) and width (m)

# files for relative elevation (above minimum dem)
relativeElevationFiles = global_30min/routing/channel_properties/dzRel%04d.nc

```

```
relativeElevationLevels = 0.0, 0.01, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60,
0.70, 0.80, 0.90, 1.00
```

```
# composite crop factors for WaterBodies:
```

```
cropCoefficientWaterNC = global_30min/routing/kc_surface_water/cropCoefficient
ForOpenWater.nc
minCropWaterKC          = 1.00
```

```
# lake and reservoir parameters
```

```
waterBodyInputNC        = global_30min/routing/surface_water_bodies/waterBodies
30min.nc
onlyNaturalWaterBodies = False
```

```
# initial conditions:
```

```
waterBodyStorageIni      = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/waterBodyStorage_1999-12-31.nc
channelStorageIni        = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/channelStorage_1999-12-31.nc
readAvlChannelStorageIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/readAvlChannelStorage_1999-12-31.nc
avgDischargeLongIni      = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/avgDischargeLong_1999-12-31.nc
avgDischargeShortIni     = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/avgDischargeShort_1999-12-31.nc
m2tDischargeLongIni      = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/m2tDischargeLong_1999-12-31.nc
avgBaseflowLongIni       = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/avgBaseflowLong_1999-12-31.nc
riverbedExchangeIni      = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/riverbedExchange_1999-12-31.nc
```

```
#
```

```
# initial condition of sub-
```

```
time step discharge (needed for estimating number of time steps in kinematic w
ave methods)
```

```
subDischargeIni          = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/subDischarge_1999-12-31.nc
```

```
#
```

```
avgLakeReservoirInflowShortIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/avgLakeReservoirInflowShort_1999-12-31.nc
```

```
avgLakeReservoirOutflowLongIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/avgLakeReservoirOutflowLong_1999-12-31.nc
```

```
#
```

```
# number of days (timesteps) that have been performed for spinning up initial
conditions in the routing module (i.e. channelStorageIni, avgDischargeLongIni,
avgDischargeShortIni, etc.)
```

```
timestepsToAvgDischargeIni = global_30min/initialConditions/non-
natural/consistent_run_201903XX/1999/timestepsToAvgDischarge_1999-12-31.nc
# Note that:
# - maximum number of days (timesteps) to calculate long term average flow val
ues (default: 5 years = 5 * 365 days = 1825)
# - maximum number of days (timesteps) to calculate short term average values
(default: 1 month = 1 * 30 days = 30)
```

```
[reportingOptions]
```

```
# output files that will be written in the disk in netcdf files:
```

```
# - annual resolution
```

```
outAnnuaTotNC = totalEvaporation, actualET, evaporation_from_irrigation,transp
iration_from_irrigation,referencePotET
```

```
# netcdf format and zlib setup
```

```
formatNetCDF = NETCDF4
```

```
zlib = True
```