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Master's Thesis
GEO 511

Climate Change and Water Power Production in Selected Power Plants in the Ticino Canton

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Acknowledgments

Wem die Dankbarkeit geniert,
der ist übel dran,
denke, der dich erst geführt,
wer für dich getan!

JOHANN WOLFGANG VON GOETHE (1749 - 1832)

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Summary

1. Introduction

Water is an essential element, not only for biological life, but also in many other respects, which allow society to function efficiently. Present day society is probably even more dependent on this resource than in the past. In the past, the mechanical use of water power was utilised for working (mills) or for commerce (rivers as trade connections). After industrialisation it became possible to produce electricity directly from water power, and today an important part of the energy supply in many countries is based on water power production.

This way of producing energy changed the Swiss landscape already many decades ago. In the Swiss Alps many dams and pipes conducting water down into the valleys were built and run-of-river plants modify the natural flow of many rivers. Due to these facilities, hydroelectric energy production provided Switzerland in 2012 with more than half its electricity requirements (58.7%, BFE 2012a).

The role of hydropower and renewable energy sources in general will become more important in the future. The European commission adopted two plans ("20-20-20 targets" for 2020 and "road map" for 2050) that promote a reduction of greenhouse gas emissions and energy consumption, an increase in energy efficiency and a major use of renewable technologies (Gaudard and Romerio 2013).

Switzerland has also adopted policies that go in the same direction. In 2011 the Federal Council formulated a new energy strategy for the next decades that is known under the name of "Energiestrategie 2050" (BFE 2013b). A main point of this strategy is the abandoning of nuclear power stations for energy production purposes. This means that the shortage of energy arising from the deactivation of nuclear plants must be replaced with other technologies. It is questionable whether nuclear power stations will be entirely replaced by renewable energy sources, but these sources will surely become more relevant in the future, and they will have to improve their contribution to Swiss energy production. For this reason the Federal Council plans further development of water power in Switzerland (BFE 2012b)

A big challenge for future developments is that the exploitation of water power is already very high and there remain only a few possibilities for the building of new dams. Nevertheless, it is theoretically possible to increase water power production by 1.5 TWh/y until 2050 under present legislation. With revised frame conditions (e.g. extension of aid money, reduction of water rates, simplification of procedures for concessions and the immediate inclusion of all stakeholders in order to improve acceptance) the increase in water production could even reach 3.2 TWh/y (BFE 2012b).

The major issue in this regard is that the building of new plants or the extension of old dams would today face more resistance than in the past, because the population's acceptance of new dams, despite the still large acceptance of hydropower production, is limited. The reason for this is that interests in energy production today are in conflict with other interests such as tourism, agriculture and nature conservation. In the future these conflicts will probably further increase as laws regulating the impact on natural environment (e.g. residual flow, fish protection) become more rigorous. Moreover, high capital investment and long amortisation costs for operators of hydropower plants make future development of hydropower in Switzerland more difficult (BFE 2008, Beniston 2010).

In this contest, the challenges that derive from climate change are only one aspect influencing future waterpower production, but they could eventually preclude the required increase in hydroelectric power production: what is the effect of climate change on runoff? Will there be enough water to guarantee enough energy production? How will the future runoff be distributed throughout the year?

This master's thesis analyses the projected changes in runoff regimes during three future periods in selected catchments of the Ticino Canton. The water of these catchments is used for water power production. The thesis is written in the context of a study assigned from the power plants operators of the Ticino Canton to the WSL Birmensdorf. In this master's thesis the following questions are analysed:

- What changes will there be in the runoff regimes of the selected catchments in the future?
- How is it possible to minimise the impact of these changes in order to optimise energy production?

Climate change impacts hydropower production in several ways. "The three main factors that determine the impact are: the annual runoff, its temporal distribution and sedimentation" (Gaudard and Romerio 2013). This master's thesis will focus on the first two factors mentioned above.

The first chapter of this master's thesis resumes the current state of research in this field with particular focus on Switzerland. The second part describes the data and the methodology. The next chapter presents the uncertainties that influence the simulations. Later, the results of the hydrological modelling are presented. The final discussion section tries to answer the second question and to put the results in a larger context, highlighting other factors that influence hydropower production (energy market, policy formulation and the role of other technologies) in a qualitative way. In conclusion, the results and interpretations of this master's thesis are summarized.

2. Current state of research

The impact of climate change on runoff in relation to hydropower plants has already been recognised as a major issue for several years, due to the economical importance of hydropower production to society. For this reason there are at present many studies on this topic. It is not always possible to compare the results of these studies because of the different data and methodologies used and because of the major differences in catchment response to climate change, even in adjacent catchments (Farinotti et al. 2012, Maran et al. 2013). Nonetheless, the main conclusions of these studies are useful in order to highlight the current knowledge on the topic and the points that are potentially controversial, and also in order to help interpret the results of simulations.

Lehner et al. (2003) investigated the potential for hydropower production in Europe at country scale, basically analysing the changes in river runoff due to climate change. The study distinguishes between reservoir and run-of-river stations, and uses population growth and gross domestic product pro capita as an indicator of electricity demand. The main conclusions of this study are that in the future there will be significant changes in runoff across Europe. In the northern regions (Scandinavia and the North of Russia) an increase in runoff between 15% and 30% is expected. In the southern regions in contrast (Portugal, Spain, Bulgaria, Turkey) there will be a marked decrease in runoff in rivers between 20% and 50% due to an evolution toward a drier climate and, in Eastern Europe, to increased water use because of the projected economic growth. The evolution of river runoff and the forecast economic development will lead to a projected overall decrease in hydropower production in Europe of about 6% by 2070. Gaudard and Romerio (2013) point out that “the Northern gains will not however compensate the Southern losses” and they confirm the findings of Lehner et al. (2003). Lehner et al. (2003) do not consider possible changes due to political decisions, but even if such predictions on continental scale are associated with large regional uncertainties, their study gives a first impression of future developments of river runoff for the whole continent.

The findings of Lehner et al. (2003) are supported by Beniston (2010). The latter identifies also a west-east band between France and the Black Sea where precipitation is expected to decrease by up to 40%. This study also predicts a probable increase in extreme precipitation events in central Europe, with associated flood risk.

There are numerous studies on variations in runoff in the Alps due to climate change. The results are in accordance with the aforementioned works: the Rhone may dry up, leading to more competition for water use (Beniston 2010). This is consistent because Switzerland is geographically in the central-southern part of Europe. Beniston et al. (2011) also propose some potential solutions for disputes that may arise between different users due to water shortages in the future (e.g. agriculture, tourism, hydropower, drinking water).

Most studies simulate future meteorological variables (temperature and precipitation) with combinations of global climate models (GCMs) and regional climate models (RCMs). The resulting data are then used to force a hydrological model. The conclusions of the different studies are mostly consistent with one another. The few discrepancies are probably due to methodological, regional and topographical differences between catchments and their different degrees of glaciated area.

Braun et al. (2000) analyse the effect of climate change in two different areas of the Alps, focusing on two different runoff regimes: the Bavarian region (nivo-pluvial regime) and the central Alps (glacial regime). Their results show that the Bavarian region reacts more strongly to changes in precipitation than to changes in temperature. For this reason it will not be affected by climate change as much as catchments in the central Alps. For glacial catchments, a first phase of increase in runoff due to melting glaciers is forecast. After this phase, runoff will decrease.

Bieri and Schleiss (2013) investigate the impact of climate change in the upper Aare region. They found that almost all glaciers will disappear by the end of the century, and confirm the findings of Braun et al. (2000) in the Aare basin. Here, the runoff regime will change to snowmelt, dominated by a peak in spring and decreasing runoff in summer.

The same trends are confirmed by Farinotti et al. (2012) who investigate the response of runoff in nine alpine catchments. They emphasise that the transition to a new regime is mainly influenced by the degree of glaciated area of the catchment, the total ice volume and the distribution of ice according to altitude. Changes in annual precipitation in the future are not really significant, and more particularly they strongly depend on the location of the catchment. Catchments with a high degree of glaciation will show a greater change in the distribution of runoff over the year. The maximal simulated runoff will occur before 2050 in all catchments.

Similar conclusions are obtained by Bernhard et al. (2011) for the Alpenrhein and Engadin catchments: reduced snow cover and increased melting of glaciers will lead first to an increase in runoff, and later to a decreased water supply. The maximum runoff in the future will be up to six weeks earlier than at present, and the period with low runoff will be longer.

Melting glaciers are also investigated by Terrier et al. (2011). The focus of their research is the appearance of new alpine lakes after the retreat of a glacier. They show it in a case study in the Corbassière region and demonstrate that “an economically interesting pumped-storage scheme could be built between the new lake Corbassière and the existing Mauvoisin reservoir” in order to face the new challenges posed by climate warming.

The link between changes in runoff and their effect on power production in the Swiss Alps is investigated by Schaefli et al. (2007). They found that global warming has a negative impact on hydropower production, leading to a decrease in energy production of up to 36% by the end of the century. They also highlight that uncertainties in regional climate response to global warming are significant, and that changes in electricity demand due to changing temperature patterns can influence the management of a power plant more than changes in runoff.

The shift in regime and the decrease in summer runoff are also confirmed by Horton et al. (2006) and Finger et al. (2012). The latter notice that heavy precipitation events in autumn can lead to increased water losses for power production due to overflow.

Different research institutions in Switzerland have published a study about climate change scenarios in Switzerland (CH2011, 2011). Future scenarios for Switzerland foresee an increase in mean temperature in all regions. Precipitation is forecast to decrease in summer and increase in winter (also for all regions). For both temperature and precipitation the magnitude of change greatly depends on societal development (represented by the emission scenario used in the study). The consequences for water power production are investigated in a study (SGHL 2011). The results show a probable decrease in production for high mountain power stations in the Valais Canton, more runoff in winter but less in summer, and a favourable situation for run-of-river plants because of more equilibrated runoff regimes throughout the year. This study also emphasises that results cannot be generalised.

There are also a few studies on the southern part of the Alps. As Maran et al. (2013) underline, response to climate change even in neighbouring catchments can be totally different. Nonetheless, conclusions from studies on catchments in the Southern Alps are more useful for this thesis than studies on the northern part because the Alps act as a barrier for meteorological events. Catchments situated in the southern part of the Alps should also have more features in common with one another than with northern catchments because of their more similar meteorological conditions: mean annual temperatures in Ticino are higher than in other parts of Switzerland. Ticino also shows very high annual precipitation compared with other Swiss regions. Their maxima are in spring (May) and autumn (September, October) (MeteoSchweiz 2013).

Ranzi et al. (2009) simulated runoff for two future periods in two basins of the Po catchment: Oglio and Lys. The simulations show a decrease in runoff (and also in power production) for both catchments of about 13-14% for the period 2079 – 2099. One reason for this decrease, among others, is the increase in forest-covered area because of the rise of the tree line and the subsequent increase in evapotranspiration that affects runoff.

A further study investigates the influence of different scenarios on runoff changes in two catchments (Ticino and Thur), but does not consider the effects on hydropower production (Jasper et al. 2004). It found that winter runoff in Ticino will increase by about 31%, whereas summer runoff will decrease by 33%. The annual mean runoff will also decrease by about 10%, but the authors emphasise the influence of different scenarios: the mean runoff change can vary from -22% to +4%! This spread reflects the big uncertainty arising from precipitation scenarios for the future. The authors also underline that changes in runoff in Ticino are largely controlled by shifts in snow conditions.

Gaudard et al. (2013) analyse future changes in runoff in the upper Rhone basin (Northern Alps), Toce and Val d'Aosta (Southern Alps), and also consider the effects of the evolution of the energy market on power plants in these regions. Annual runoff is projected to increase in the Toce basin and decrease in the other two catchments, showing once more the high variability between neighbouring regions. Runoff changes will influence electricity production, but market prices will determine the management strategy of power plants in order to maximise revenue.

Finally, Hänggi and Weingartner (2012) analysed the climatic variations over the past century and their impact on runoff volumes. Their conclusions are consistent with the previous studies presented here: in glaciated catchments there was a strong increase in runoff, while in lower altitude regions there is now more runoff in winter and less in summer compared with the past. The total volume of water over one year remained similar to the past. For this reason, energy production in Switzerland has grown over the past decades. Hänggi and Weingartner (2012) find in addition that changes in the Alpine areas are more significant for hydroelectric energy production than changes in lower areas because 60 – 70% of total energy production occur in Alpine areas, and also because the elevation-dependent potential for energy production is higher in these regions.

3. Methodology and data

Catchment characteristics

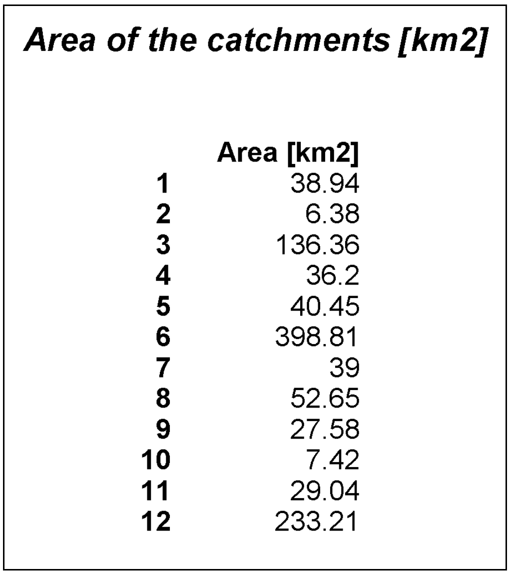
In this master's thesis, the runoff of twelve catchments that collect water for water power production purposes is analysed. Each catchment is associated with a MeteoSwiss meteorological station that measures temperature and precipitation in a daily time steps. I regret that it does not read as smoothly as it might, but as this thesis was written in the context of a study assigned by the power plant operators of the Ticino Canton, it was necessary to make all catchment's locations anonymous. Catchments and stations are shown in Figure 1:

Catchment	Station
1:	Monte Bre
2:	Monte Generoso
3:	San Bernardino
4:	Bellinzona
5:	Grono
6:	Piotta
7:	Grono
8:	Olivone
9:	Cimetta
10:	Piotta
11:	Piotta
12:	Cimetta

Figure 1: The twelve analysed catchments (blue hues) and the meteorological stations of MeteoSwiss (red points) with corresponding labels (labelled rectangles). The coupling of meteorological stations and catchments is listed in the upper left corner of the map

The following table illustrates the area of the different basins:

Table 1: Area of the selected catchments



Area of the catchments [km2]

	Area [km2]
1	38.94
2	6.38
3	136.36
4	36.2
5	40.45
6	398.81
7	39
8	52.65
9	27.58
10	7.42
11	29.04
12	233.21

Table 1 illustrates the different surface areas of the catchments. They range from very small catchments such as catchment 2 with an area of 6.38 Km^2 to much bigger catchments such as catchment 6, with an area of 398 Km^2. The combination of meteorological stations poses therefore some challenges. In catchment 2 the area of the catchment is small, and there is a meteorological station near the catchment. Catchment 6 is much bigger and more varied: a part of the valley has a west-east orientation, and the other part extends more towards the south-east. Within this catchment and on its border there are three meteorological stations, and the challenge is to decide which one is the most adequate to simulate the whole region.

Moreover, each of these areas has a complex infrastructure to collect and use water for hydropower purposes. The different facilities include run-of-river plants, transfer tunnels, hydroelectric power stations with reservoir (dam) and pumped storage systems. Figure 2 shows the facilities in the region of Airolo to illustrate this complexity.

Figure 2: Overview of hydropower facilities in the region of Airolo (www.e-dric.ch)

Figure 2 shows that even if runoff forms in a catchment, it is possible that it may not flow entirely from the outlet of the same catchment. There can be transfer tunnels that conduct the waters out of the catchment, or tunnels conducting water in from outside the catchment. This can make the interpretation of runoff simulations very difficult, because water power production could depend in part on runoff changes outside of the analysed catchment. This obviously complicates the association of the catchment with a meteorological station. For this reason it is first assumed that all runoff formed in one catchment flows to its outlet and that no water is transported there from outside. This assumption should not influence the results because meteorological stations in adjacent catchments should give similar simulations of temperature and precipitation changes. This will however be reviewed after having analysed the results of the simulation of temperature and precipitation.

Coupling a meteorological station to a catchment

The purpose of coupling each catchment with a meteorological station is to better account for the different characteristics of the individual regions. The mountainous topography of the Ticino Canton makes it difficult to choose an optimal coupling of stations and catchments, because meteorological conditions can show a high variability even in a very small spatial area. The variability of temperature and precipitation inside a catchment can be very high because of the deep valleys. Not all the meteorological stations are in an analysed catchment but even if this were the case, it is not certain whether this fact would be representative for the whole area.

With the awareness of this problem, each catchment was coupled here to its nearest station, except in some cases where other factors were considered more important. These factors may be the influence of natural barriers between the meteorological station and the catchment or the difference of height between them. These exceptions concerned catchments 3, 6 and 11:

- The distance between the meteorological stations of S.Bernardino and Grono from catchment 3 is very similar. S.Bernardino was preferred because of the more similar height.
- Three meteorological stations are suitable for catchment 6: Piotta, Airolo in the catchment and the station on Mount Matro near its southern end. Piotta was assigned to this catchment because of its central position in the valley compared to Airolo and Mount Matro.
- Catchment 11 is geographically closer to the station of Piotta than Airolo but the difference in height (Piotta = 1000 m.a.s.l., Airolo = 1200 m.a.s.l., catchment 11 – height of the dam = 1800 m.a.s.l.) suggests that Airolo could have more similar meteorological conditions than Piotta.

Finally, the meteorological station of Olivone was assigned to catchment 8. This is the best available meteorological station. However it could be possible that a station on the Grisons side of the Alps would better reflect the meteorological conditions of the Greina plain where catchment 8 is mostly situated.

Table 2: Analysed catchments, related abbreviations used in this master's thesis and associated meteorological stations

Catchment	Meteorological Stations
1	Monte Bre
2	Monte Generoso
3	San Bernardino
4	Bellinzona
5	Grono
6	Piotta
7	Grono
8	Olivone
9	Cimetta
10	Piotta
11	Airolo
12	Cimetta

Climatological data

The daily scenarios of temperature and precipitation change for the meteorological stations are provided by C2SM (http://data.c2sm.ethz.ch/dataset/ch2011/). They are projected changes relative to the mean annual cycle between a reference period (1980-2009) and three future scenario periods: 2021-2050 (in the following: "2035"), 2045-2074 (in the following: "2060") and 2070-2099 (in the following: "2085"). The calibration period for the simulations was set from 1984 to 1989, while the period 1990-1996 served as the validation period.

The simulations were carried out for each scenario period using three different emission scenarios: A1B, A2 and RCP3PD. Each emission scenario is the description of a possible future evolution of greenhouse gas emissions and therefore of our world's living conditions:

- The A1B scenario describes a "world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies." This scenario predicts a balanced use of fossil and non-fossil energy sources (IPCC 2000).
- The A2 scenario describes a world with continuously growing population and with slower technological change (IPCC 2000).
- The RCP3PD scenario is the "optimistic" scenario. It describes a world that has succeeded in limiting greenhouse gas emissions, and where climate warming is limited to about 2°C by the end of the century.

The simulations are operated using an ensemble of ten combined global climate models (GCM) and regional climate models (RCM), model chains run by different European institutes. This ensemble-chains are listed in Table 3:

Table 3: The ensemble-chains of regional and global climate models used in this study for the simulations of future temperature and precipitation.

Institute	GCM	RCM
ETHZ	HadCM3Q0	CLM
HC	HadCM3Q0	HadRM3Q0
SMHI	HadCM3Q3	RCA
SMHI	ECHAM	RCA
MPI	ECHAM	REMO
KNMI	ECHAM	RACMO
ICTP	ECHAM	REGCM
DMI	ECHAM	HIRHAM
CNRM	ARPEGE	ALADIN
SMHI	BCM	RCA

The C2SM data set is explicitly intended for studies on changes in the mean annual cycle of temperature and precipitation, and it is not suitable for analyses of future extreme events because the projections are calculated on mean precipitation and temperature changes over a 30-year period (CH2011, 2011).

The simulations are calculated based on measured data (control period 1980-2009) using the delta change approach. “The delta change method is a transformation that scales historical (...) time series to obtain series that are representative for a future climate” (Kraaijenbrink 2013).

This method predicts future temperatures, adjusting observed daily temperatures by adding the difference between the time horizon and the reference period predicted by a climate model. In a similar manner the predicted precipitation is obtained by multiplying measured daily precipitation by the ratio between time horizon predicted by a climate model and the reference period (Chen et al. 2011).

In this approach, the control run is by definition equal to the observed precipitation and temperature. (Teutschbein and Seibert 2010). The main disadvantage of this method is that it does not modify future variability of temperature and precipitation occurrence. This is obviously not realistic. Therefore for some purposes as flood research or extreme events the delta change approach is not useful (Teutschbein and Seibert 2010, Chen et al. 2011). However, for trend research it represents a good and widely accepted method, and is easy to implement.

The simulations of C2SM for the three scenario periods obtain different results for both variables of temperature (Figure 3-5) and precipitation (Figure 6-8) depending on the model used. These simulations are now presented.

Temperature

The following figures display the simulations for the station of Airolo as an example for all stations. The graphs for all other stations are in the attached memory stick.

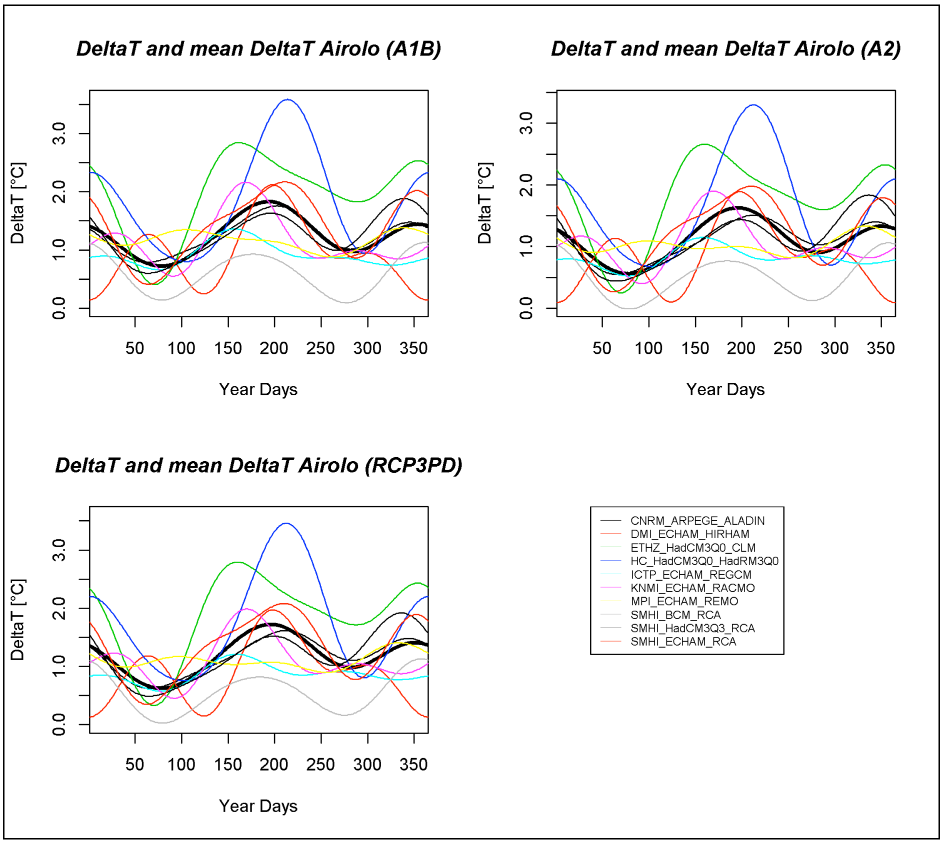


Figure 3: Thirty-year average changes in temperature (DeltaT, coloured lines) and average of the simulations of 10 different GCM-RCM-chains (mean DeltaT, bold line) for the meteorological station of Airolo (scenario period 2021-2050)

Figure 3 shows the simulations of temperature changes with respect to the control period (1980 – 2009) based on a thirty-year average. The DeltaT represents the difference of temperature between the control period and the scenario period (in Figure 3: 2021 – 2050). The coloured lines represent the simulations of the different regional climate models. The bold line is the average of the ten simulations calculated with the regional climate models.

For scenario period 2021 – 2050 all simulations in all emission scenarios show a small increase in temperature of 1.2°C, 1.1°C and 1.2°C for the emission scenarios A1B, A2 and RCP3PD respectively. The projections of the ten regional climate models are quite different: for “Aladin” the increase in temperature is generally less significant than for the other models over the whole year. “HadRM3Q0” on the other hand, simulates a much larger increase in temperature in summer. “CLM” generally predicts a larger increase in temperature with respect to the other models, except in winter. The differences between the simulations result from differences in the model’s programming.

In scenario period 2021 – 2050 the different emission scenarios do not have a big influence on simulated climate warming: all three scenarios generate a similar increase in temperature.

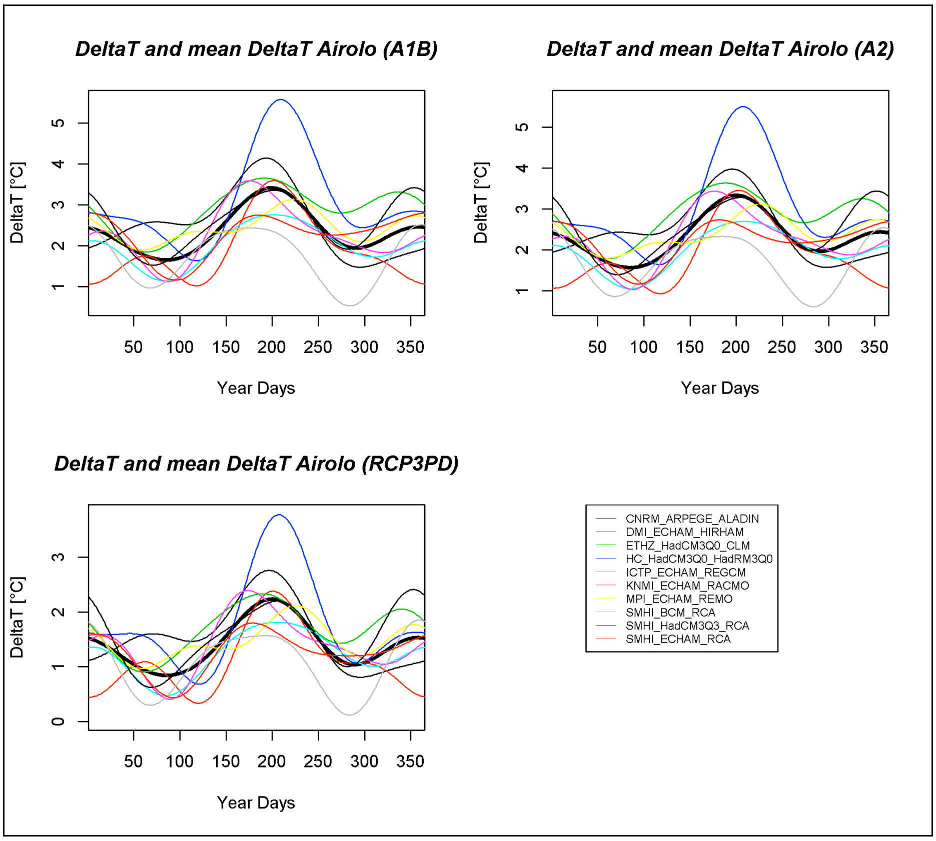


Figure 4: Thirty-year average changes in temperature (DeltaT, coloured lines) and average of the simulations of 10 GCM-RCM-chains (mean DeltaT, bold line) for the meteorological station of Airolo (scenario period 2045-2074)

In scenario period 2045 – 2074 (Figure 4) the projected increase in temperature (average of the ten regional climate models) is 2.4°C (A1B), 2.3°C (A2) and 1.4°C (RCP3PD) respectively. “HadRM3Q0” still simulates a greater increase in summer temperature than all other models. On the contrary “CLM” gives results more similar to the other models.

In this scenario period we already see that emission scenario RCP3PD produces simulations with a smaller increase in temperature up to 0.7°C (in summer even 1.2°C) with respect to the scenarios A1B and A2, which still give similar results. The range of the warming (average of all the model’s simulations) is 0.8 – 2.2°C for scenario RCP3PD and 1.5 – 3.4°C for scenarios A1B and A2. The growing amplitude of this range with respect to scenario period 2021 – 2050 reflects a growing uncertainty of the projections in time.

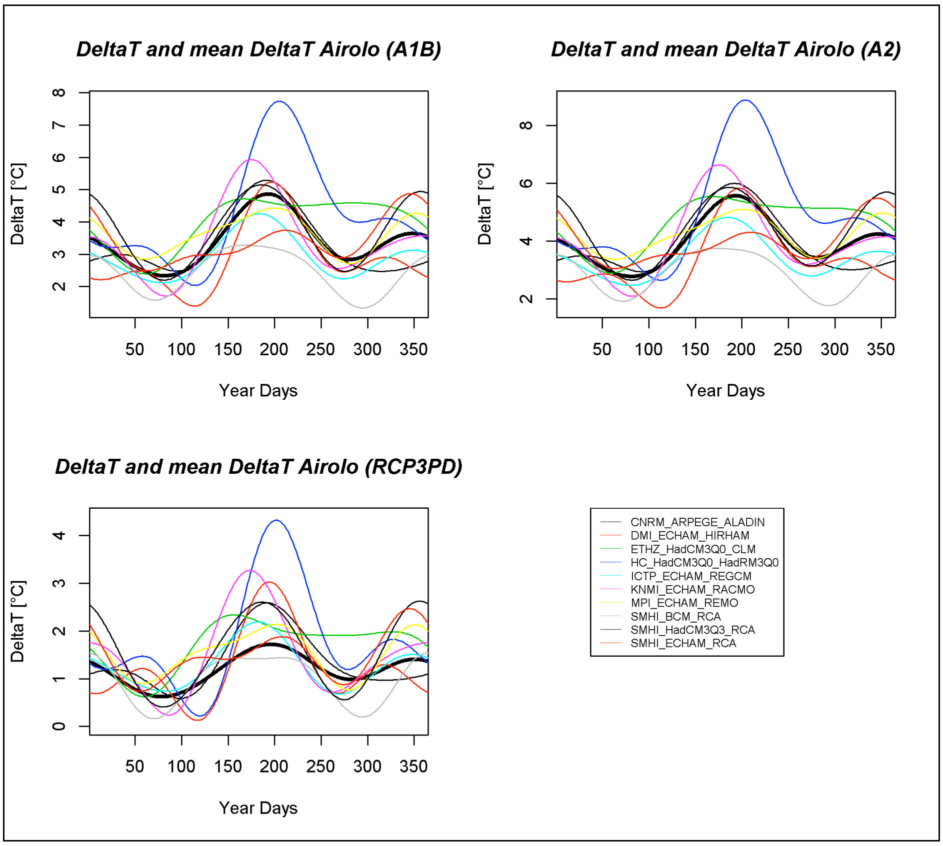


Figure 5: Thirty-year average changes in temperature (DeltaT, coloured lines) and average of the simulations of 10 different GCM-RCM-chains (mean DeltaT, bold line) for the meteorological station of Airolo (scenario period 2070-2099)

In scenario period 2085 (Figure 5) we see differences between the simulations of all emission scenarios: warming in a world following emission scenario RCP3PD will remain approximately at the levels of the year 2060. The highest increase in temperature in 2085 is expected under emission scenario A2 with a mean yearly increase of 4°C.The increase under emission scenario A1B (yearly average 3.4°C) is more moderate but still significant. This is consistent with the definition of the different emission scenarios.

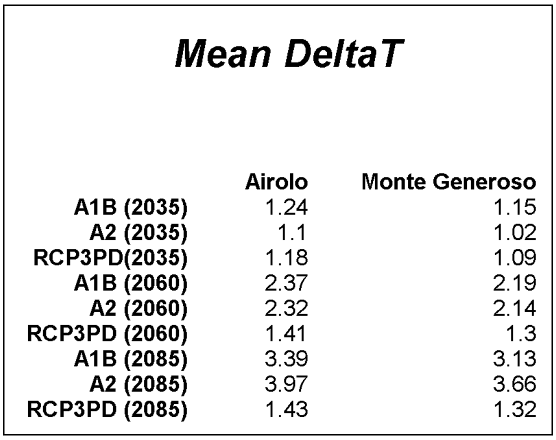
In general it is possible to see an increase in mean temperature over the whole year in all scenario periods and for all emission scenarios. This increase is more pronounced in summer. In winter it is also possible to observe an increase in temperature but more moderate than in summer, whereas in spring and autumn the increase is less pronounced than in the other two seasons. In all years and emission scenarios “HadRM3Q0” (blue line) simulates a distinctly higher peak in summer temperature than all other RCMs.

It is also interesting to observe that the influence of the rapid introduction of new technologies mitigating the greenhouse effect has a visible impact on rising temperatures only from scenario period 2060.

Finally, the results of the projections are quite similar for all meteorological stations used in this study. There are slight differences in simulated temperature changes between stations in the northern part of

Ticino and others in the southern part. Table 4 shows these differences between the stations of Airolo (as an example for the North) and Monte Generoso (as an example for the South):

Table 4: Thirty-year average of temperature increase (Mean DeltaT) calculated with respect to the control period (1980 – 2009) for the meteorological stations of Airolo and Monte Generoso (all scenario periods and all emission scenarios)



Mean DeltaT

	Airolo	**Monte Generoso**
A1B (2035)	1.24	1.15
A2 (2035)	1.1	1.02
RCP3PD(2035)	1.18	1.09
A1B (2060)	2.37	2.19
A2 (2060)	2.32	2.14
RCP3PD (2060)	1.41	1.3
A1B (2085)	3.39	3.13
A2 (2085)	3.97	3.66
RCP3PD (2085)	1.43	1.32

As apparent in table 4, the differences in simulated temperature amount to 0.1°C for scenario period 2035 and to about 0.2°C and 0.3°C for scenario period 2060 and 2085 respectively. The differences are small in absolute terms, but they still represent more than 7% of the total increase in temperature for scenario period 2070 – 2099, and can therefore slightly influence the projections for runoff.

Precipitation

One representative station (Airolo) has been chosen to show the projected changes for precipitation (DeltaP). The changes are expressed in percent and represent the difference between the projected precipitation for a given scenario period with respect to the control period. Also for this variable, the changes in DeltaP vary slightly between the stations, but the main conclusions are similar for all regions.

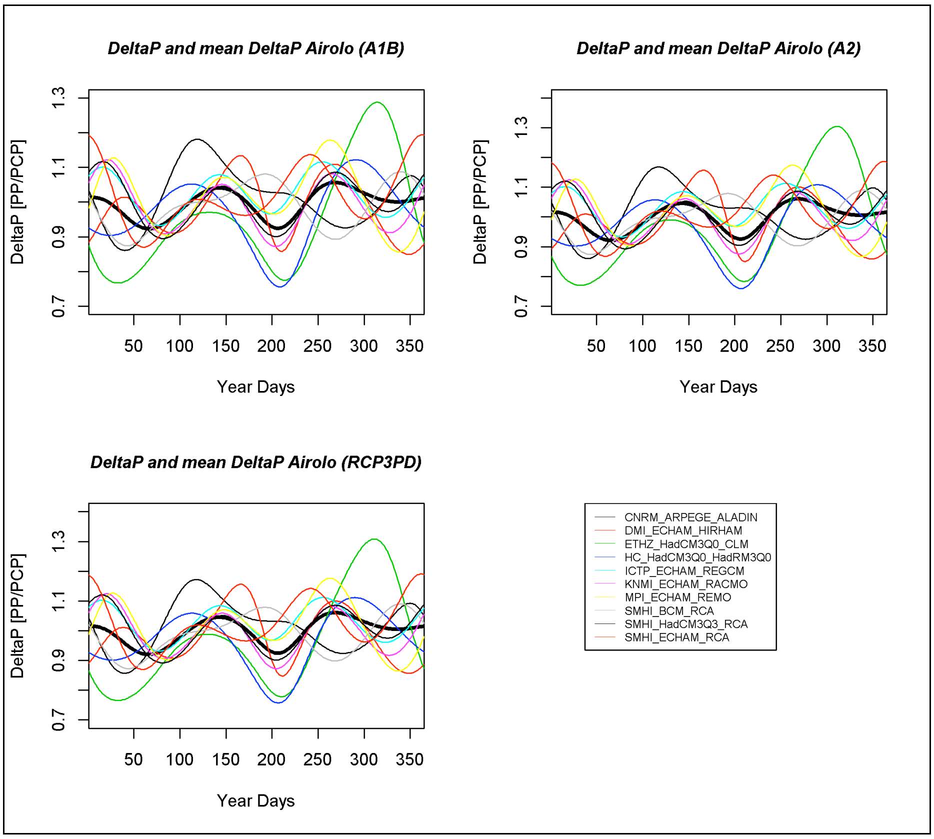


Figure 6: Thirty-year average changes in precipitation (DeltaP, coloured lines) and average of the simulations of 10 different GCM-RCM-chains (mean DeltaP, bold line) for the meteorological station of Airolo (scenario period 2021 – 2050). [PP = Predicted Precipitation, PCP = Precipitation Control Period]

For scenario period 2021 – 2050 (Figure 6) changes in precipitation over one year are not projected to change much. The yearly average of simulated precipitation in the near future scenario still lies between 99.4 – 99.7% of the control period. Precipitation is projected to be slightly more significant in winter and spring, whereas summer precipitation is projected to decrease. The simulations of CLM are overestimated around October with respect to the mean of all models (bold line), whereas during winter the simulations are generally underestimated.

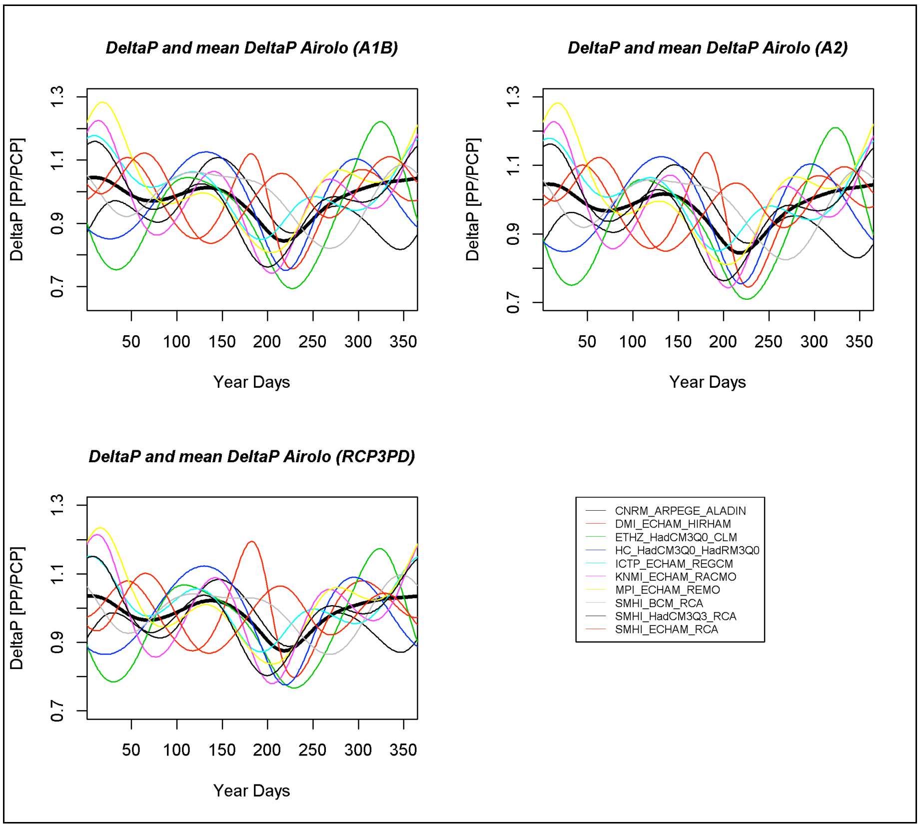


Figure 7: Thirty-year average changes in precipitation (DeltaP, coloured lines) and average of the simulations of 10 different GCM-RCM-chains (mean DeltaP, bold line) for the meteorological station of Airolo (scenario period 2045 – 2074). [PP = Predicted Precipitation, PCP = Precipitation Control Period]

In Figure 7 the decrease in summer precipitation becomes more significant using all three emission scenarios. This fact also influences the yearly average, which for this period falls to 97.6% for emission scenarios A1B and A2 and to 98.3% for emission scenario RCP3PD.

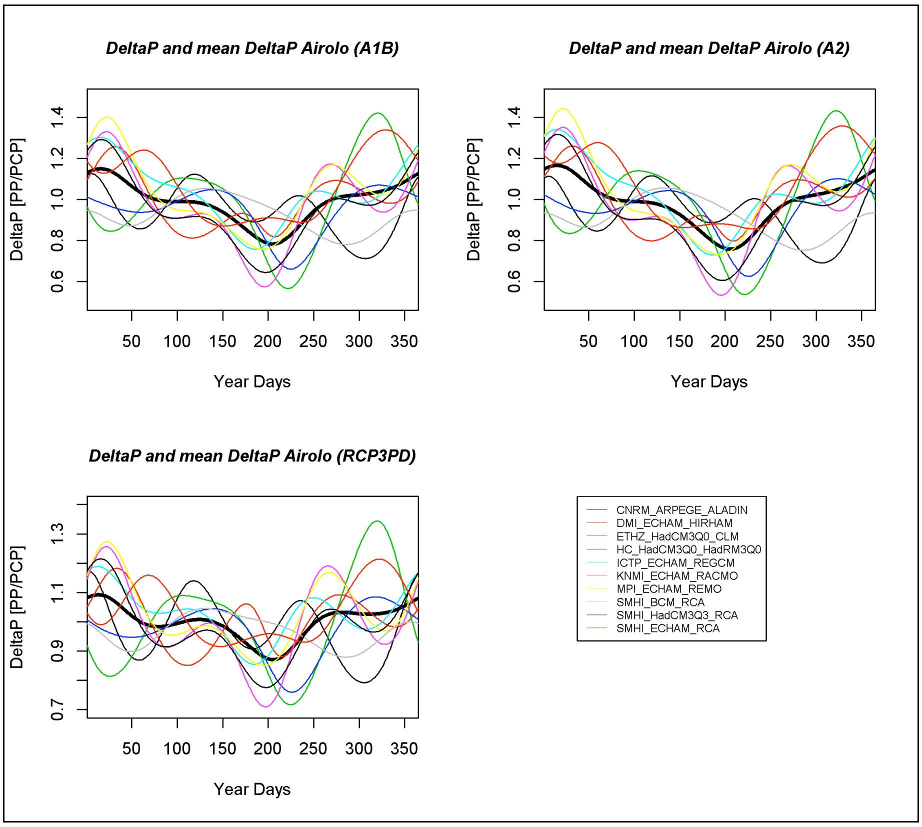


Figure 8: Thirty-year average changes in precipitation (DeltaP, coloured lines) and average of the simulations of 10 different GCM-RCM-chains (mean DeltaP, bold line) for the meteorological station of Airolo (scenario period 2070 – 2099). [PP = Predicted Precipitation, PCP = Precipitation Control Period]

The simulations for scenario period 2070 – 2099 (Figure 8) confirm the trends that emerged in the preceding periods: precipitation is projected to diminish in summer and increase in winter, but yearly precipitation does not show a significant change. Mean yearly precipitation in this period is projected to be 98.5%, 98.2% and 99.8% for emission scenario A1B, A2 and RCP3PD respectively. Following emission scenario RCP3PD the quantity of simulated precipitations remains the same as the control period, and the differences following the other two emission scenarios are in fact greater, but effectively still small.

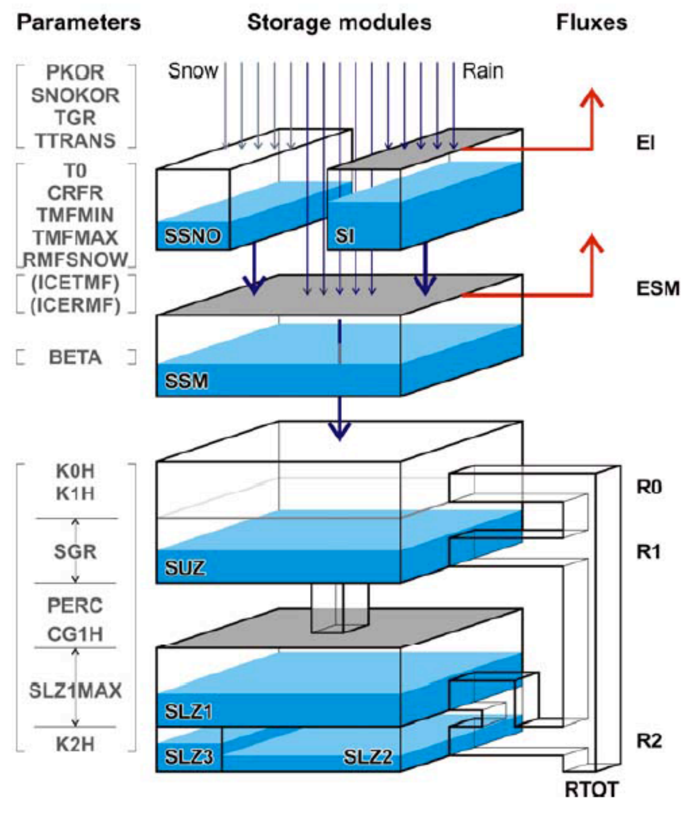
The simulations for all other stations are included in the attached memory stick. The only relevant difference between all meteorological stations is that the diminution in precipitation in summer in Airolo is less pronounced than in the stations situated in South Ticino (e.g.: Monte Generoso or Stabio), probably due to the proximity to the Alps. Changes in precipitation in Airolo are forecast to vary between 75-117% of current precipitation. In comparison the range of variation for the period 2070 – 2099 for the station of Monte Generoso is 55 – 122%, meaning that in summer there will be nearly only half as much precipitation as at the present time.

Going back to the previous assumption regarding the origin of water (pages 15 – 16) it is now admissible to maintain it. There are some small differences between the simulations of the different meteorological stations of both temperature and precipitation, but these differences are not related to adjacent stations. For this reason they will not influence the coupling of meteorological stations with catchments.

Hydrological model

The climatological data of temperature and precipitation are used to force the hydrological model PREVAH (Precipitation-Runoff-Evapotranspiration-Hydrotope model). The modelling system PREVAH has been developed to allow good simulations in mountainous regions where the high spatial and temporal variability of climatic events and the very different types of morphology, soil and vegetation of the territory present more challenges than in other areas. Moreover, the relevant processes are formulated with conceptual approaches and therefore do not need high computational resources (Viviroli et al. 2007).

Figure 9 shows the different modules of the model and the different parameters that necessitate a



	PARAMETERS
	Precipitation
PKOR	Precipitation adjustment for rain [%]
SNOKOR	Precipitation adjustment for snow [%]
TGR	Threshold temperature rain-snow [°C]
TTRANS	Transition temperature range rain-snow [°C]
	Snowmelt
T0	Threshold temperature snowmelt [°C]
CRFR	Coefficient for re-freezing [-]
TMFMIN	Minimum temperature melt factor for snow [mm d^{-1} K^{-1}]
TMFMAX	Maximum temperature melt factor for snow [mm d^{-1} K^{-1}]
RMFSNOW	Constant radiation melt factor snow [mm h^{-1} K^{-1} W^{-1} m^{2}]
	Icemelt (glaciated catchments only)
ICETMF	Constant temperature melt factor for ice [mm d^{-1} K^{-1}]
ICERMF	Constant radiation melt factor for ice [mm h^{-1} K^{-1} W^{-1} m^{2}]
	Soil moisture recharge
BETA	Non-linearity parameter for infiltration module [-]
	Runoff formation
K0H	Storage time for surface runoff [h]
K1H	Storage time for interflow [h]
SGR	Threshold for quick runoff formation [mm]
PERC	Percolation rate [mm h^{-1}]
CG1H	Storage time for quick baseflow [h]
SLZ1MAX	Maximal content of the quick baseflow storage [mm]
K2H	Storage time for slow baseflow [h]
	STORAGE MODULES
SSNO	Snow storage [mm]
SI	Interception storage [mm]
SSM	Soil moisture storage [mm]
SUZ	Upper zone (unsaturated) runoff storage [mm]
SLZ1–3	Lower zone (saturated) runoff storages [mm]
	FLUXES
EI	Evaporation from interception storage [mm h^{-1}]
ESM	Evapotranspiration from soil moisture storage [mm h^{-1}]
R0	Quick runoff (surface runoff) [mm h^{-1}]
R1	Delayed runoff (interflow) [mm h^{-1}]
R2	Slow runoff (baseflow) [mm h^{-1}]
RTOT	Total runoff [mm h^{-1}]

Figure 9: Diagram of PREVAH's model core (From: Viviroli et al. 2007)

The parameters can be subdivided into the following groups: adjustment of water balance, differentiation of solid and liquid precipitation, snowmelt module, glacier module, soil moisture module, runoff generation module. The time interval used in this study is one day.

The calibration of the model is based on a combination of three efficiency scores (linear and logarithmic Nash-Sutcliffe efficiency, and volumetric deviation) with three temporal viewpoints (entire calibration period, annual and monthly variation). The outcome of the combination of these three scores is the total skill of the model. To get an optimal set in PREVAH, the parameters are automatically calibrated in pairs. Firstly, a parameter space is defined setting maxima and minima for each parameter, then the parameter space is subdivided into nine sections and the overall score of the parameter values at the intersections are compared. After this the best parameter will become the centre of the reduced parameter space. The process is repeated in several ways until a satisfying pair of parameters is detected (Viviroli et al. 2007)..

For this study a fully-distributed version of PREVAH was used (Viviroli et al. 2009). This version has a spatial resolution of 200 metres. A more detailed description of the model structure can be found in Viviroli et al. (2009). The overview of the model can be found in Bernhard and Zappa (2012).

Choice of variables to analyse

Following the equation of water balance:

$$P = Q + E + \Delta S$$

for the purpose of this master's thesis, the most interesting variables among all variables considered in PREVAH are precipitation (P), runoff (Q), Evaporation (E) and the storage in the soil layers (ΔS).

Runoff is defined as "the water volume per time unit ([m^3/s^{-1}] or [l/s^{-1}]) that leaves a catchment through a surface runoff profile (e.g. river profile) and possibly also through subsurface ways." (Viviroli et al. 2007) The conceptualisation of runoff formation in PREVAH consists of storage reservoirs in different soil layers (Figure 10). The parameters K_0, K_1 and Perc can be tuned empirically or through model calibration. They control the generation of surface runoff, interflow and deeper percolation in the saturated zone respectively (Viviroli et al. 2007).

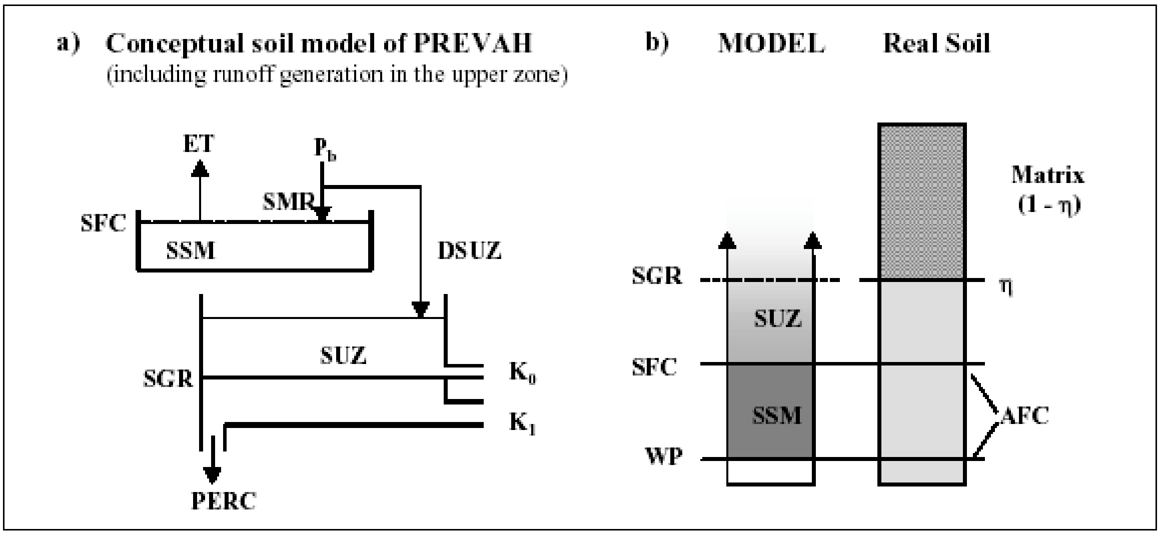


Figure 10: conceptual model of runoff generation in PREVAH (from: Viviroli et al. 2007)

In this thesis it is possible to directly consider total runoff (in PREVAH: RGES), because this is a good representation of the amount water that can be used for water power purposes.

PREVAH calculates different types of evapotranspiration (in the output referred to simply as "evaporation"): evaporation from interception storage, from soil, total potential evaporation and total real evaporation. Potential evaporation is the amount of evaporation that occurs if sufficient water is available in the soil. Potential evaporation serves as basis for the computation of real evaporation. The latter is adjusted "to actual moisture, soil and vegetation conditions at the location of focus" (Viviroli et al. 2007), and therefore also considers interception evaporation and soil evaporation.

PREVAH also calculates different types of flow from each storage reservoir (Figure 10), from interception and from snow. The most important form of storage for the purposes of this master's thesis is the storage of snow, because it influences the distribution of runoff over the year. Storage in glaciers is not of relevance in the selected catchments.

4. Uncertainties

Methodological uncertainty

Uncertainty in hydrology arises on the one hand from the imperfect knowledge or information of the analysed system, and on the other hand from the random nature of most events (Solomatine and Wagener 2011). Solomatine and Wagener (2011) identify the following sources of uncertainty in hydrological models:

- The conceptual representation of the watershed and its translation into numerical form in the model.
- Uncertainty of data caused by measurement errors or data processing.
- Simplification in the description of real-world processes.
- Uncertainty of parameter estimation (e.g. equifinality).

Some uncertainties cannot currently be reduced because of a lack of knowledge. Other sources will probably never be completely removed. Even if this kind of uncertainty persists, a proper estimation of uncertainty is vital to facilitate a risk-based approach to decision-making (Kay et al. 2008).

Different authors found that the most significant source of uncertainty in simulations of temperature and precipitation is represented by the different GCMs (Kay et al. 2008, Chen et al. 2011, Prudhomme and Davies 2008, Déqué et al. 2007). In general, uncertainty related to modelling of the future climate is larger than that related to hydrological modelling (Kay et al. 2008). This outcome is confirmed by Schaefli (2005), who found that uncertainties of climate evolution simulations (depending on uncertain global mean warming and regional response to climate change) contribute much more to the total uncertainty of predicted runoff than uncertainty related to the hydrological model.

The approach of this master's thesis, which considers a combination of different GCMs and RCMs, accounts for the uncertainty arising from each individual model. This uncertainty is visualised by the difference range of all previsions. This combination represents the best current scientific knowledge in the field of climate modelling. This ensemble approach is recommended by several authors in order to avoid biased modelling results and to include inter-model variability (Prudhomme and Davies 2008, Teutschbein and Seibert 2010, Finger et al. 2012). Moreover, the median between all model projections "may provide better runoff simulation results" than the single model projection (Teutschbein and Seibert 2010, Jacob et al. 2007).

The parameter set is a source of uncertainty because there can be different optimal parameter sets. This characteristic is known as equifinality. An analysis of these different sets would highlight the uncertainty arising from the choice of different parameter sets (Horton et al. 2006). However this uncertainty is much smaller than the uncertainty arising from GCMs and RCMs, as highlighted by Schaefli (2005).

Other unconsidered variables

There are also variables that influence future runoff but that are not considered in this master's thesis:

Natural variables

- Changes in vegetation cover due to climate warming: Verbunt (2005) found that surface runoff will strongly decrease because of increasing forest area. This effect is greater during the growing season, not only due to increased evapotranspiration, but also because of increased storage of water in the canopy. However, this effect diminishes with increasing altitude, because soil depths and also plant roots are smaller, leading to reduced evapotranspiration compared to the lowland regions.
- The variations in debris transport in the analysed rivers with respect to the present day are not considered. Debris flow can obstruct reservoirs and damage turbines and hence cause costs to the operator of the power plant. Several studies (e.g. SGHL 2011, Pralong et al. 2011) forecast a slight diminution in the mean debris transport in the future in the majority of rivers in the Valais Canton. The diminution is due to the smaller runoff projected in future periods and the consequently decreased capability of the rivers for debris transport. It is also possible to assume that the conditions for hydropower production will not deteriorate in the future.

Anthropogenic variables

- Competition from other renewable energy carriers (e.g. wind and solar energy, biomass). The rapid increase of electricity production from wind and solar facilities generates lower spot prices and a diminution of the spread between peak and off-peak prices (Gaudard and Romerio 2013). A smaller spread means less revenue for operators of hydropower plants. This means in turn that projects for new plants or investments in existing hydropower plants become less attractive.
- Length and boundary conditions of new concession periods
- New technologies for energy storage (photovoltaic, battery)
- Changes in the political dimension (e.g. changes related to the "Energiestrategie 2050" and its implementation)

5. Results

Because the climatological data of C2SM showed some differences in simulations between catchments in the northern and others in the southern part of Ticino, two catchments were chose as examples in order to assess these differences: catchment 11 in the north (coupled with the climatological data of Airolo) and catchment 2 in the south (coupled with the data of Monte Generoso).

Overview

The next figures show the simulations for corrected precipitation, real evapotranspiration, total runoff, glacier and snowmelt for catchments 2 and 11 over the three scenario periods. Coloured lines indicate the yearly sum for each different emission scenario. The black lines are the values of the control period.

Finally, the simulations are ordered by probability of occurrence subdividing a Gaussian function of probability in quartiles (L=low, M=middle, U=up). The middle quartiles in the Gaussian distribution have a higher probability of occurrence. For this reason they will be the reference for commentaries.

Catchment 11 (North Ticino)

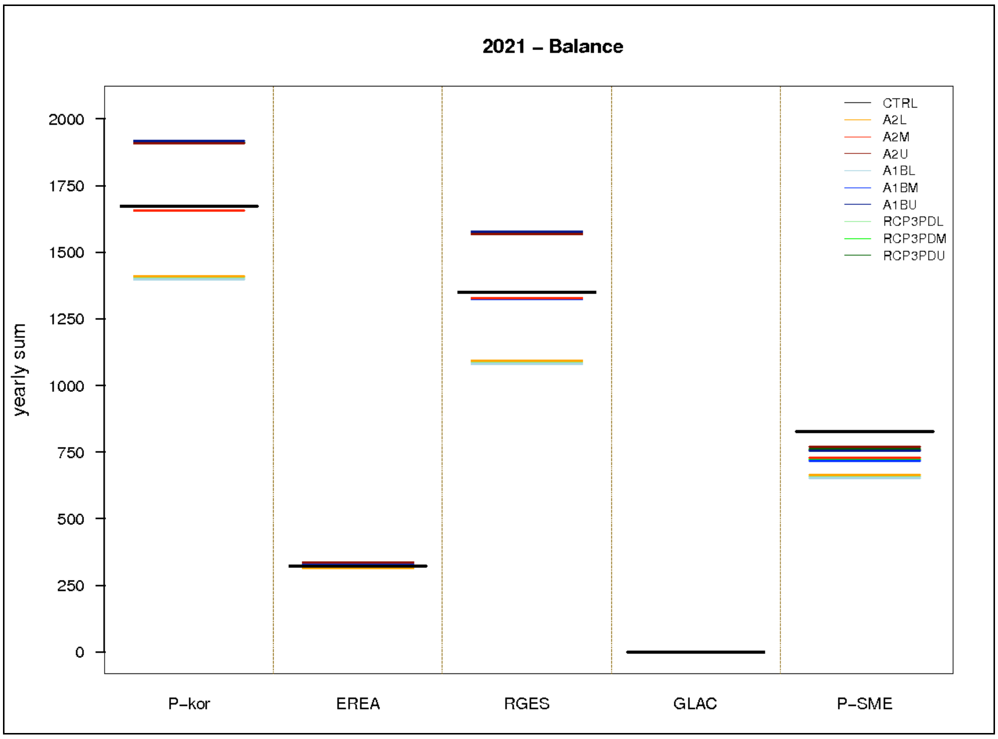


Figure 11: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 11 in scenario period 2021 – 2050

As evident in figure 11, melt water from glaciers (“GLAC”) does not play a significant role in the analysed catchments because there are only seven very small glaciers in Ticino. For this reason this variable will not be considered. Real evapotranspiration is projected to remain constant over all scenario periods and will not therefore influence runoff.

In the near future period, all simulations already indicate a decrease in snowmelt. Evapotranspiration remains on similar levels compared to the control period, whereas simulations of total runoff and precipitation are more uncertain: the middle quartiles remain at the levels of the control period, but the range between upper and lower quartiles is significant.

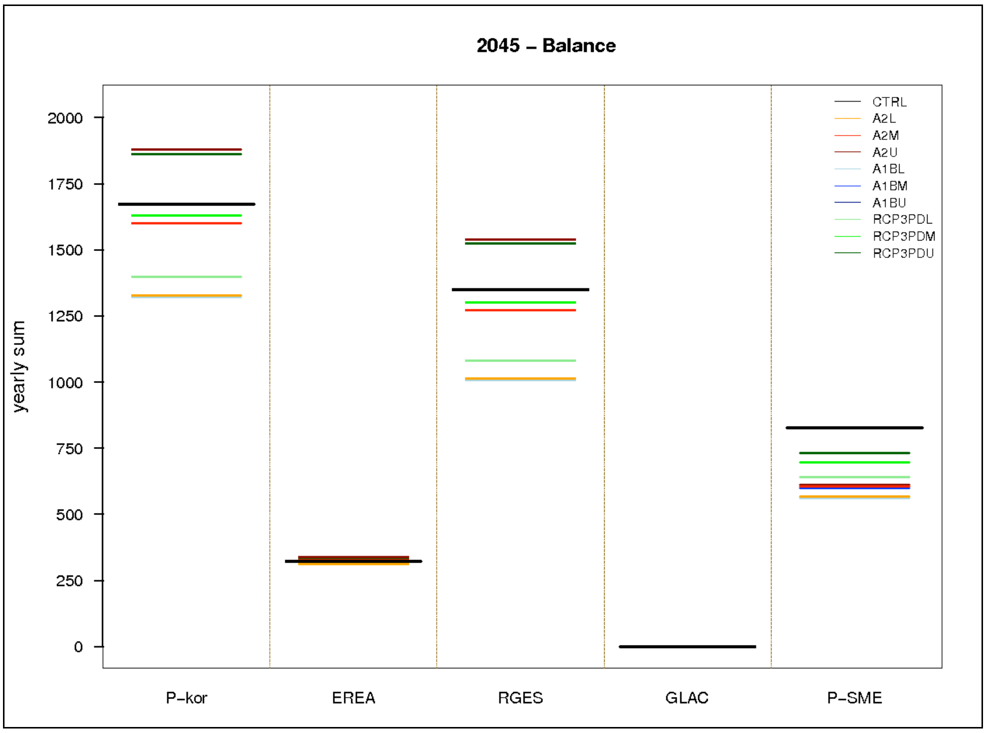


Figure 12: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 11 in scenario period 2045 – 2074

In the mid-century period (Figure 12), simulated snowmelt shows a further diminution and also total runoff and precipitation tend to diminish. The range between upper and lower quartiles remains big, but the middle quartiles (highest probability of occurrence) decrease slightly.

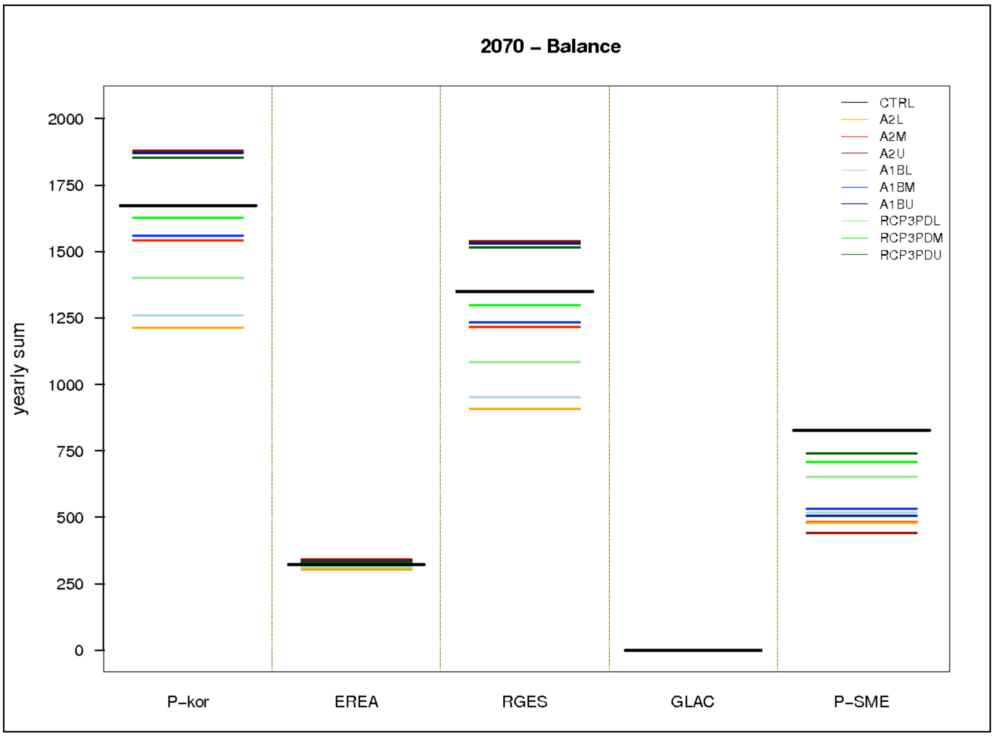


Figure 13: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 11 in scenario period 2070 – 2099

The simulations of snowmelt (Figure 13) also show a continuous diminution in scenario period 2070 – 2099. Whereas in the middle future period the differences between the emission scenarios were not pronounced, in the last scenario period (2070 – 2099) it can clearly be seen that the diminution reflects the augmentation in temperature of the climatological data, with the lowest diminution in scenario RCP3PD and the maximum diminution in scenario A2.

The most interesting variable for hydropower production is the total runoff and its distribution over the year. Its development agrees with the simulations on corrected precipitation. The middle quartiles of the simulations show a diminution of runoff in all emission scenarios: for scenario period 2070 – 2099 of 3.7 % according to emission scenario RCP3PD, and using the other two scenarios A1B and A2 of 8.4% and 9.8% respectively. However, the spread of the different simulations is high: extreme values (“U”-simulations) indicate that even larger runoff quantities than in the control period could be possible in the future.

Catchment 2 (South Ticino)

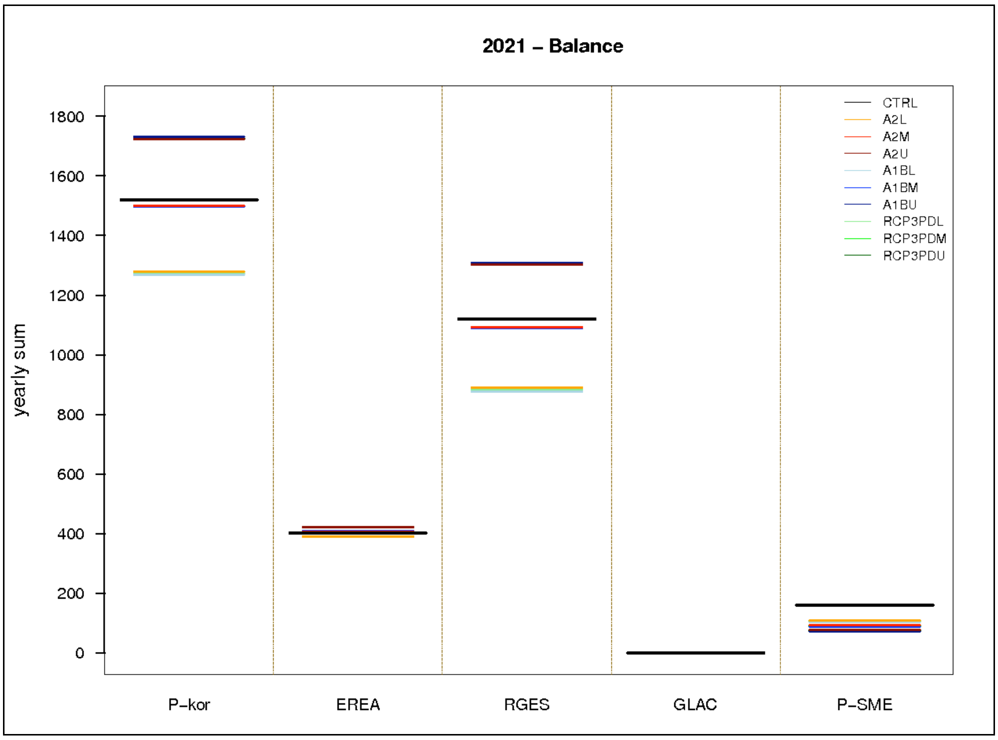


Figure 14: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 2 in scenario period 2021 – 2050

The results for catchment 2 (figure 14) are similar to the previous result for catchment 11: there is no glacier meltwater and the evapotranspiration is projected to remain stable throughout all scenario periods. The range between lower and upper quartiles of the simulations is also significant in this region. Compared to the near future in catchment 11, in catchment 2 it is already possible to observe a slight diminution in both precipitation and runoff in the middle quartiles. The diminution of snowmelt is also clear.

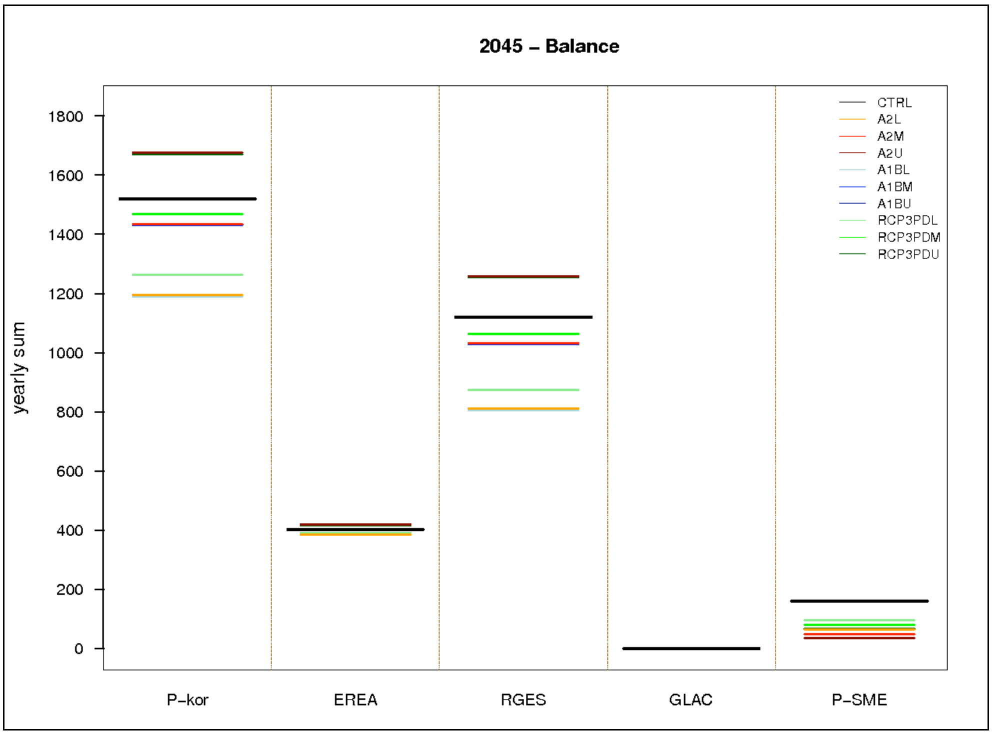


Figure 15: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 2 in scenario period 2045-2074

The mid-century period (figure 15) confirms the changes simulated in the near future period with a further diminution in precipitation, runoff and snowmelt, with the latter tending to zero.

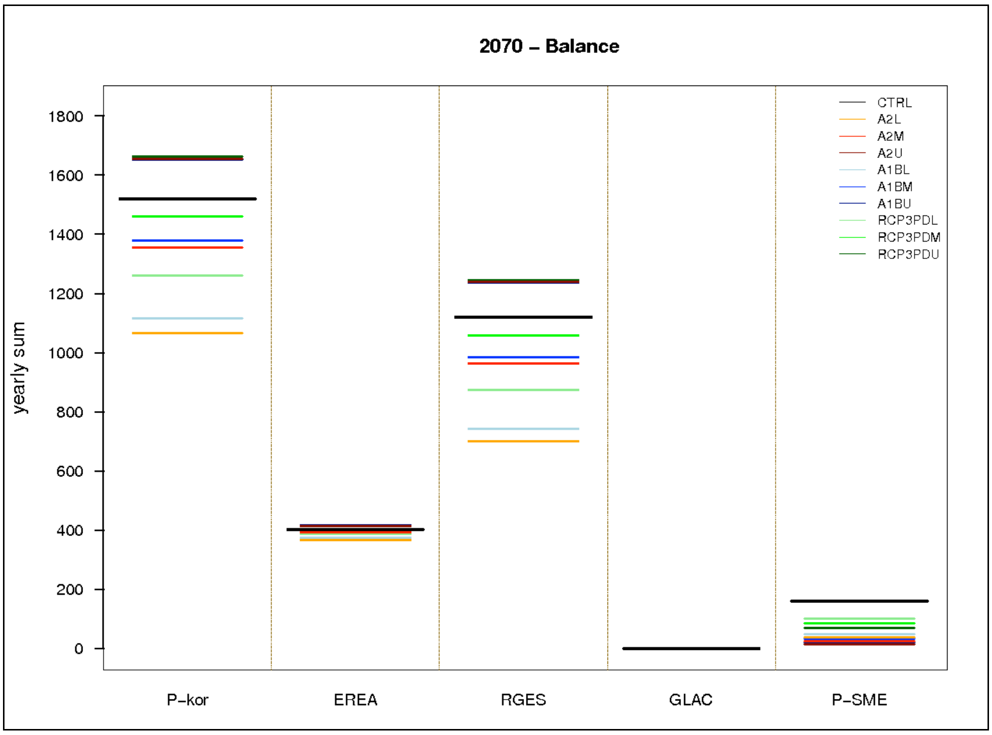


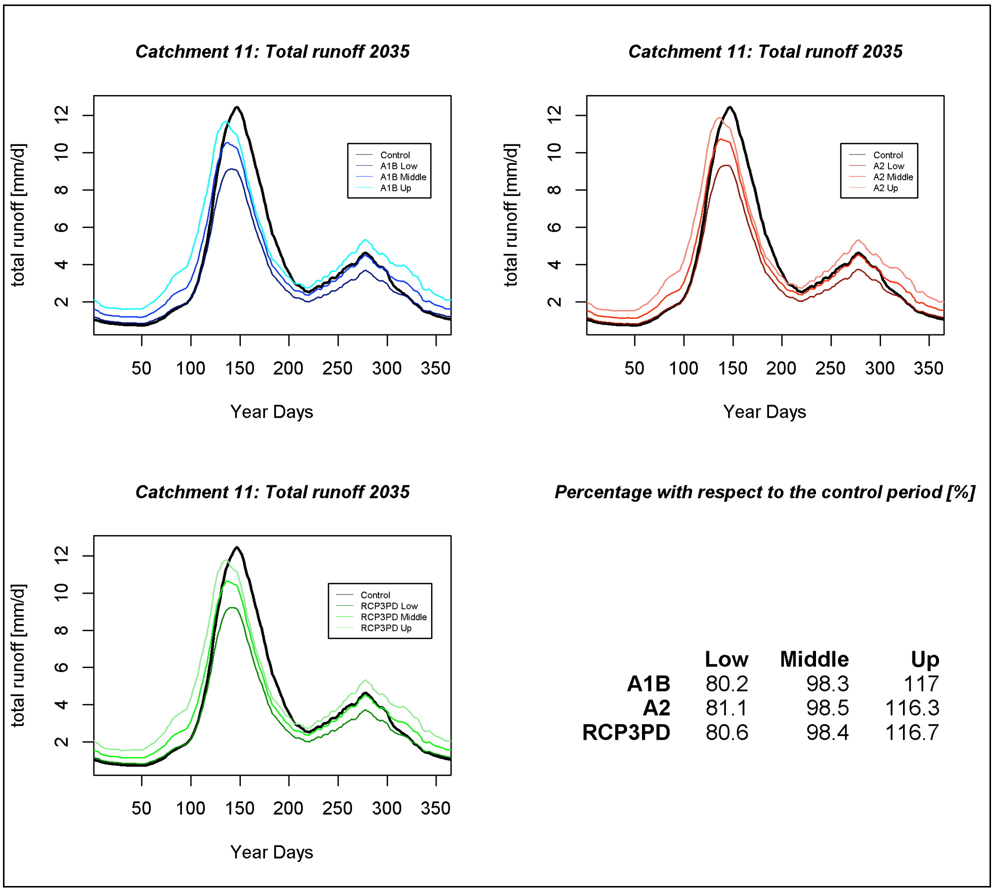
Figure 16: Thirty-year average simulations for emission scenario A1B (blue), A2 (red), RCP3PD (green) ordered by Gauss-quartiles (L=low, M=middle, U= up) with respect to the control period (black bold) for corrected precipitation [mm/d] (P-kor), real evapotranspiration [mm] (EREA), total runoff [mm] (RGES), ice melt [mm] (GLAC) and snowmelt [mm] (P_SME) for catchment 2 in scenario period 2070-2099

A comparison between the two catchments shows that the results for snowmelt and real evaporation are similar, with snowmelt almost disappearing in catchment 2 by the end of the century. The simulated diminution in total runoff (middle quartiles) in catchment 2 for the scenario period 2085 is 12.1% for the scenario A1B, 13.9% for the scenario A2 and 5.4% for the scenario RCP3PD. It is therefore apparent that the percental diminution in runoff will be more significant in catchment 2 than in catchment 11. The difference between both catchments is 3.7%, 4.1%, and 1.7% for the emission scenarios A1B, A2 and RCP3PD respectively (scenario period 2070 – 2099).

Distribution over the year

The next figures show the same results as in the previous chapter, but indicate in addition the yearly distribution of projected runoff and the percental changes with respect to the control period.

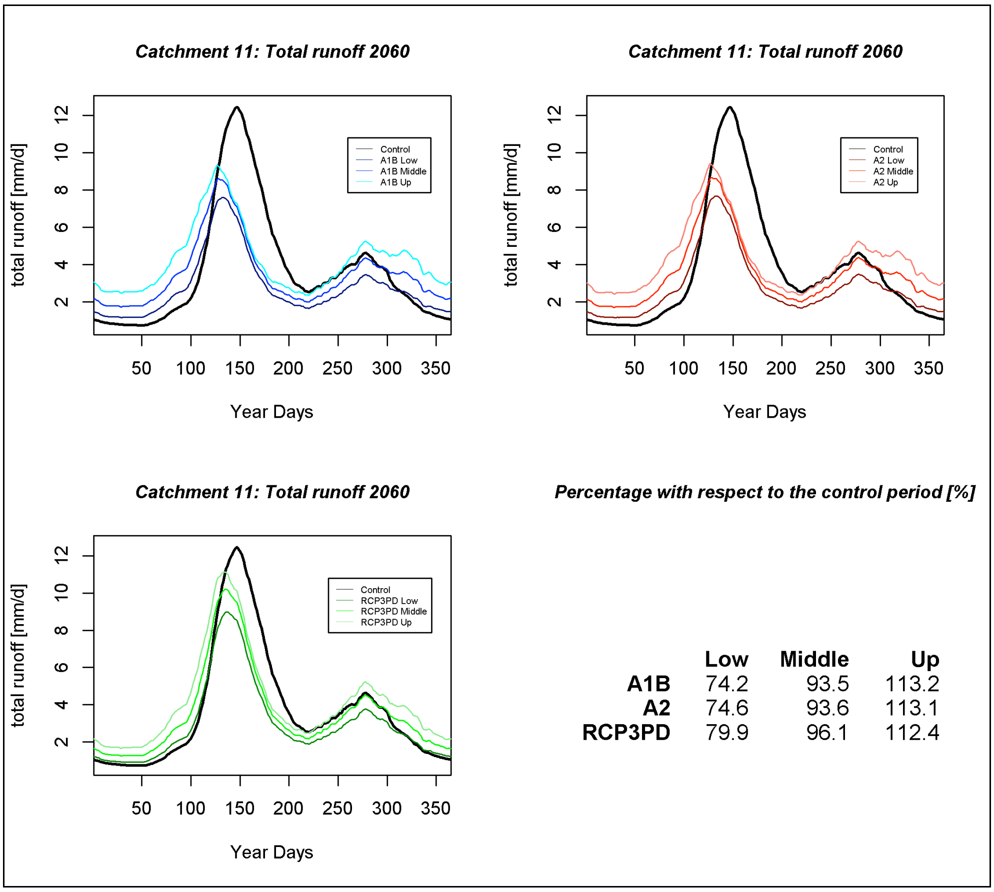
Catchment 11 (North Ticino)



	Low	Middle	Up
A1B	80.2	98.3	117
A2	81.1	98.5	116.3
RCP3PD	80.6	98.4	116.7

Figure 17: Thirty-year average simulations of total runoff in catchment 11 in scenario period 2021 – 2050 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

In the near future period (figure 17) the results are similar for all emission scenarios: runoff is projected to decrease in summer and increase in winter. Yearly mean runoff is projected to slightly decrease for the middle quartiles of the simulations (highest probability of occurrence) by 1.6 – 1.7 %, depending on the emission scenarios used. The range between lower and upper quartiles is high and reflects the uncertainty of simulations of future precipitation in mountain areas.

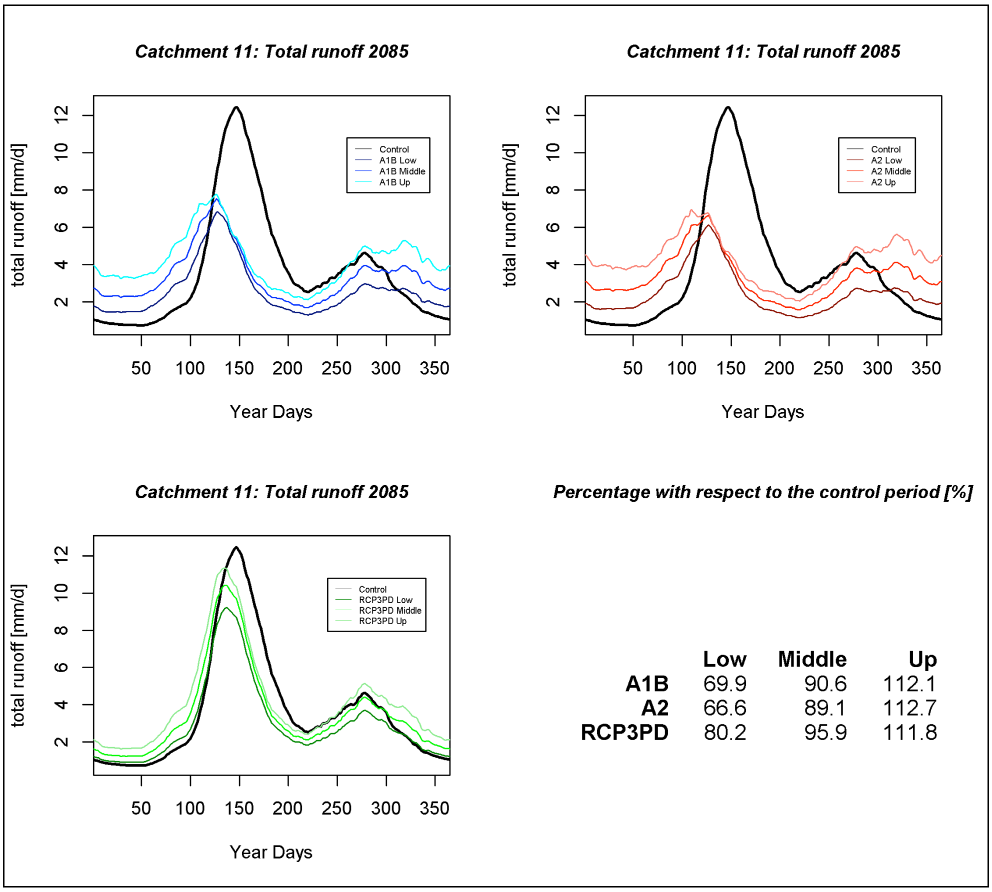


Percentage with respect to the control period [%]

	Low	Middle	Up
A1B	74.2	93.5	113.2
A2	74.6	93.6	113.1
RCP3PD	79.9	96.1	112.4

Figure 18: Thirty-year average simulations of total runoff in catchment 11 in scenario period 2045 – 2074 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

The variability of the simulations remains high also in the middle of the century (figure 18). Lower quartiles forecast a strong diminution in yearly runoff, whereas upper quartiles show a big increase. In the middle quartiles (highest probability of occurrence) the diminution in yearly runoff is more pronounced than in the near future scenario. Emission scenarios A1B and A2 give similar results, with a significant decrease in runoff during the summer peak and a general increase during the cold season. The simulations using emission scenario RCP3PD show a more stable situation: the diminution in summer is less pronounced.

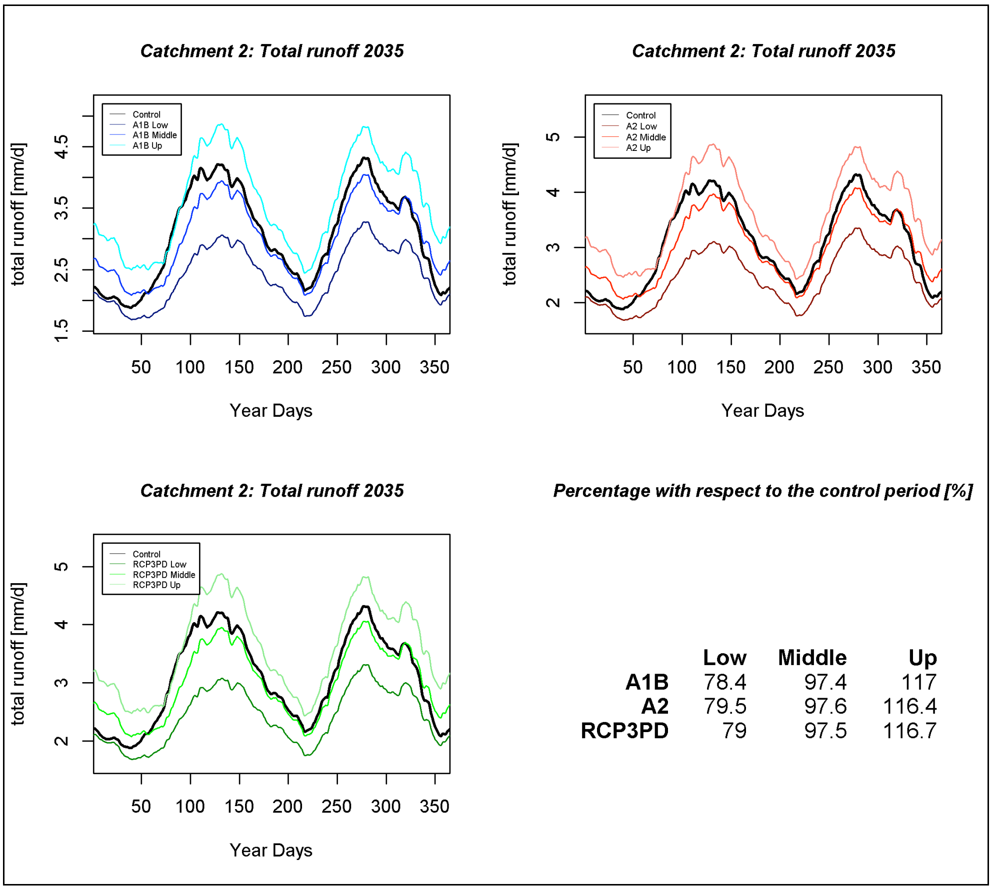


	Low	Middle	Up
A1B	69.9	90.6	112.1
A2	66.6	89.1	112.7
RCP3PD	80.2	95.9	111.8

Figure 19: Thirty-year average simulations of total runoff in catchment 11 in scenario period 2070 – 2099 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

The simulations for the end of the century (figure 19) show stable runoff values for emission scenario RCP3PD, with a small decrease in summer and a small increase during winter. The peak in runoff is smaller with respect to the control period and happens more than three weeks earlier following emission scenarios A1B and A2. The simulations for emission scenarios A1B and A2 are similar: the big runoff peak due to snowmelt in late spring will be much smaller towards the end of the century, and it is comparable in magnitude to the second peak in autumn. The total yearly runoff for the middle quartiles of the simulations (highest probability of occurrence) is 90.6 % and 89.1 % for emission scenario A1B and A2 respectively.

Catchment 2 (South Ticino)

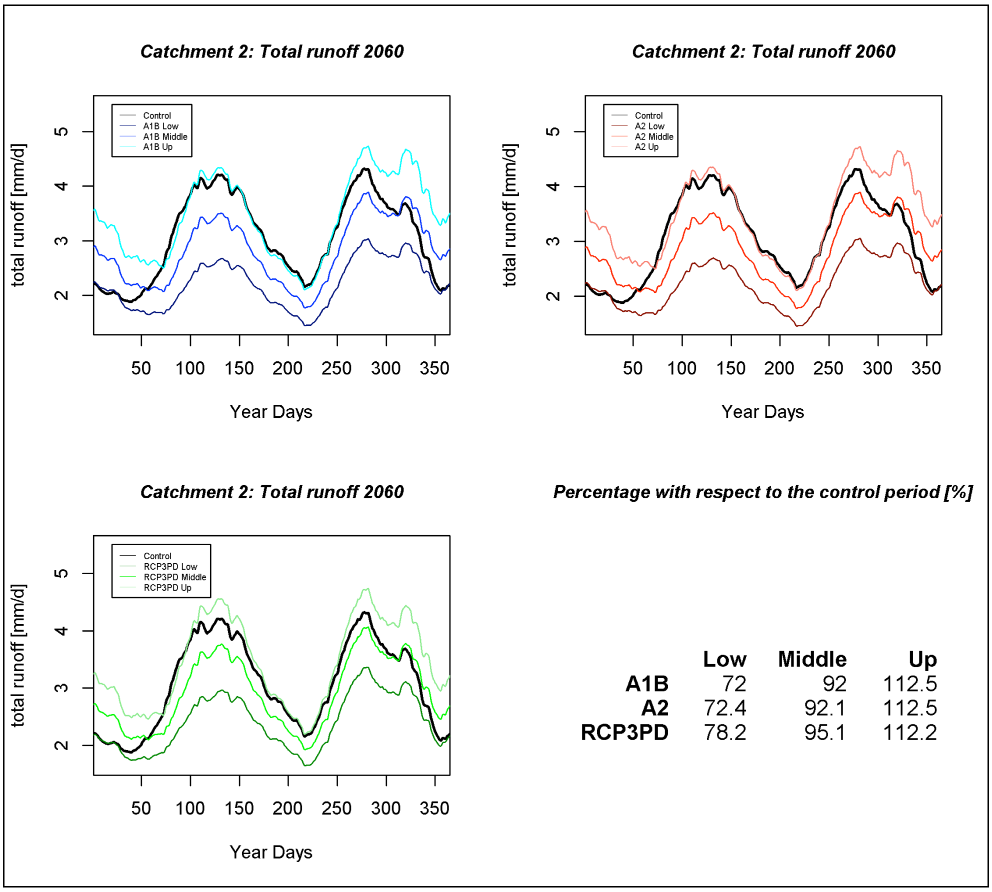


	Low	Middle	Up
A1B	78.4	97.4	117
A2	79.5	97.6	116.4
RCP3PD	79	97.5	116.7

Figure 20: Thirty-year average simulations of total runoff in catchment 2 in scenario period 2021 – 2050 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

In figure 20 it is possible to see a large difference between catchments in the northern and others in the southern part of Ticino. The runoff maximum in catchment 11 happened in late spring because of snowmelt, and in this catchment there was another peak in runoff later in autumn. This runoff regime is known in Switzerland as “nivo-pluvial méridional”. The second peak is by far less significant than the first one. In catchment 2 however the two peaks are similar with respect to the amount of water, and they cover a longer period of time. This corresponds to the runoff regime “pluvio-nival méridional.

The simulations for the near future in catchment 2 show a slight diminution in runoff during the two peaks in spring and autumn, and an increase in runoff in winter. Total runoff is projected to decrease slightly more than in catchment 11 for the same simulation period.

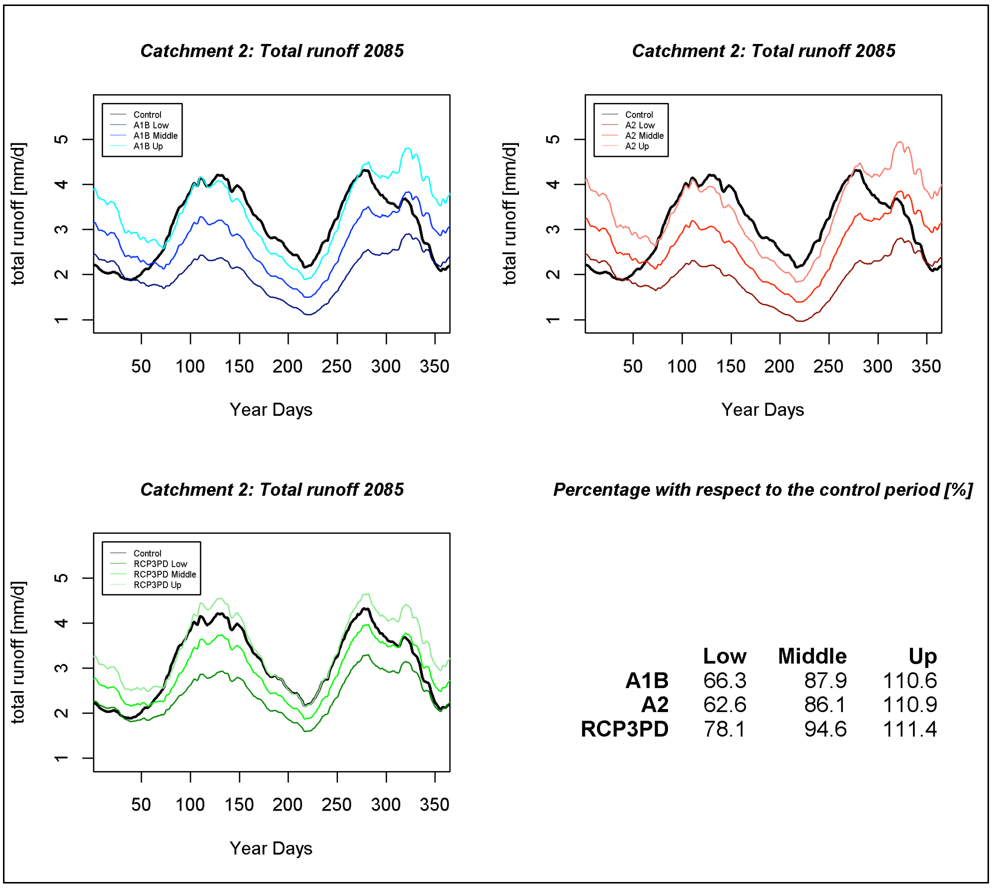


Percentage with respect to the control period [%]

	Low	Middle	Up
A1B	72	92	112.5
A2	72.4	92.1	112.5
RCP3PD	78.2	95.1	112.2

Figure 21: Thirty-year average simulations of total runoff in catchment 2 in scenario period 2045 – 2074 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

In figure 21 total runoff shows a further decrease. Losses in runoff between March and October become more significant, and the increase in winter cannot compensate them. In emission scenario RCP3PD the decrease in runoff between August and October is less pronounced, and therefore yearly runoff decreases by only 4.9%.


Catchment 2: Total runoff 2085

Catchment 2: Total runoff 2085

Catchment 2: Total runoff 2085

Percentage with respect to the control period [%]

	Low	Middle	Up
A1B	66.3	87.9	110.6
A2	62.6	86.1	110.9
RCP3PD	78.1	94.6	111.4

Figure 22: Thirty-year average simulations of total runoff in catchment of 2 in scenario period 2070 – 2099 for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to the control period (black), and changes in runoff (percent) with respect to the control period

The trends shown during the near and middle future periods for scenario A1B and A2 are confirmed in figure 22 also for scenario period 2070 – 2099. Runoff is projected to diminish further between March and October. The winter increase also becomes more pronounced. Following emission scenario RCP3PD runoff will remain similar to scenario period 2045 – 2074.

In general, the simulated changes in runoff in the two catchments chosen as examples are similar, with an augmentation in runoff in winter and a diminution in summer. The winter gain in runoff can be partly explained by higher temperatures: precipitation will fall more frequently in liquid form and will not be stored over the winter. This obviously means that snowmelt in spring will be less significant, and therefore explains the diminishing peak in late spring.

The main difference between the two catchments is that the diminution in late spring is much more significant for catchment 11 than for catchment 2 because runoff in the northern part of Ticino is much more dependent on snowmelt. The fact that snow cover is projected to drastically diminish over this century is important in many respects. On the one hand, meltwater will diminish, consequently impacting the amount of runoff in late spring; on the other hand snowmelt will boost runoff earlier in spring.

The range of the simulations (between the “L”-,”M”- and “U”-quartiles) also shows the major dependence of the runoff on snowmelt in catchment 11. Simulations of snow cover are generally less uncertain than simulations of precipitation. For this reason the spread between simulations of runoff in spring/summer is much smaller in Ritom than in Lugano, where runoff depends mainly on precipitation.

Recapitulation of runoff changes for all catchments

The next tables display the changes in runoff with respect to the control period for all catchments analysed in this master’s thesis, and considering only the middle quartiles of the simulations, which have the highest probability of occurrence:

Table 5: percental (left-hand table) and absolute (right-hand table) diminution in runoff with respect to the control period in all twelve catchments and all scenario periods for emission scenario A1B

Percentage diminution [%]

	2035	**2060**	**2085**
1	2.7	8.1	12.3
2	2.6	8	12.1
3	2.4	7.2	10.9
4	2.5	8	12.5
5	2.2	7.4	11.6
6	2.3	6.8	9.8
7	2.1	7.2	11
8	2	6.1	8.5
9	2.2	6.5	9.4
10	2.1	6.5	9.4
11	1.7	5.8	8.4
12	1.9	6.5	10.2

Absolute diminution [mm/y]

	2035	**2060**	**2085**
1	-29	-88	-133
2	-30	-90	-135
3	-33	-99	-151
4	-30	-95	-147
5	-27	-92	-144
6	-30	-89	-129
7	-27	-90	-139
8	-29	-86	-119
9	-26	-77	-111
10	-28	-86	-123
11	-23	-78	-113
12	-34	-116	-181

For emission scenario A1B (table 5), the diminution in runoff lies between 1.7 – 2.7% for the near future scenario, 5.8 – 8.1% for the middle future scenario and 8.4 – 12.5% for the scenario period 2070 – 2099.

Table 6: percental (left-hand table) and absolute (right-hand table) diminution in runoff with respect to the control period in all twelve catchments and all scenario periods for emission scenario A2

Percentage diminution [%]

	2035	2060	2085
1	2.4	8	14.1
2	2.4	7.9	13.9
3	2.2	7	12.6
4	2.2	7.9	14.5
5	1.9	7.2	13.4
6	2.1	6.6	11.2
7	1.9	7	12.8
8	1.8	6	9.7
9	2	6.4	10.8
10	1.9	6.4	10.9
11	1.5	5.6	9.8
12	1.7	6.4	11.8

Absolute diminution [mm/y]

	2035	2060	2085
1	-26	-86	-153
2	-26	-88	-155
3	-30	-97	-175
4	-26	-93	-170
5	-24	-90	-168
6	-27	-87	-148
7	-24	-88	-162
8	-26	-84	-137
9	-23	-75	-128
10	-25	-84	-143
11	-20	-76	-132
12	-30	-113	-211

For emission scenario A2 (table 6), the diminution in runoff lies between 1.7 – 2.4% for the near future scenario, 5.6 – 8% for the middle future scenario and 9.7 – 14.5% for the scenario period 2070 – 2099.

Table 7: percental (left-hand table) and absolute (right-hand table) diminution in runoff with respect to the control period in all twelve catchments and all scenario periods for emission scenario RCP3PD

Percentage diminution [%]

	2035	2060	2085
1	2.5	4.9	5.4
2	2.5	4.9	5.4
3	2.3	4.4	5
4	2.4	4.8	5.4
5	2	4.4	5
6	2.2	4.2	4.6
7	2	4.3	4.8
8	1.9	3.8	3.9
9	2	4	4.3
10	2	3.9	4.1
11	1.6	3.4	3.7
12	1.8	3.9	4.3

Absolute diminution [mm/y]

	2035	2060	2085
1	-27	-53	-59
2	-28	-55	-61
3	-32	-61	-69
4	-28	-56	-63
5	-26	-55	-62
6	-29	-56	-60
7	-25	-54	-60
8	-27	-53	-55
9	-24	-47	-51
10	-27	-51	-54
11	-21	-46	-49
12	-32	-69	-77

For emission scenario RCP3PD (table 7), the diminution in runoff lies between 1.6 – 2.5% for the near future scenario, 3.8 – 4.9% for the middle future scenario and 3.7 – 5.4% for the scenario period 2070 – 2099.

The projected changes in runoff are similar for all catchments. The biggest changes happen in catchments situated in the southern part of Ticino (1 and 2) which is consistent with the climatological data employed for simulations. The difference between catchment 11 and catchment 2 as examples of a northern and a southern catchment is 0.9%, 2.2% and 3.7% (for scenario period 2035, 2060 and 2085 respectively) in emission scenario A1B; 0.9%, 2.3%, 4.1% in emission scenario A2; and 0.9%, 1.5%, 1.7% in emission scenario RCP3PD.

Snowmelt

The importance of snowmelt has been already mentioned. In this chapter this element will be further analysed.

Jasper et al. (2004) emphasised that changes in runoff in the Ticino Canton will strongly depend on the evolution of snow storage and snowmelt. Changes in snow storage and snowmelt are shown in the next figures (23 – 24). As before, two examples were chosen: one catchment for the northern part of Ticino (10) and a second catchment for the southern part (2). Scenario period 2079 – 2099 was chosen, as the changes in snow storage and snowmelt in that period are clearer.

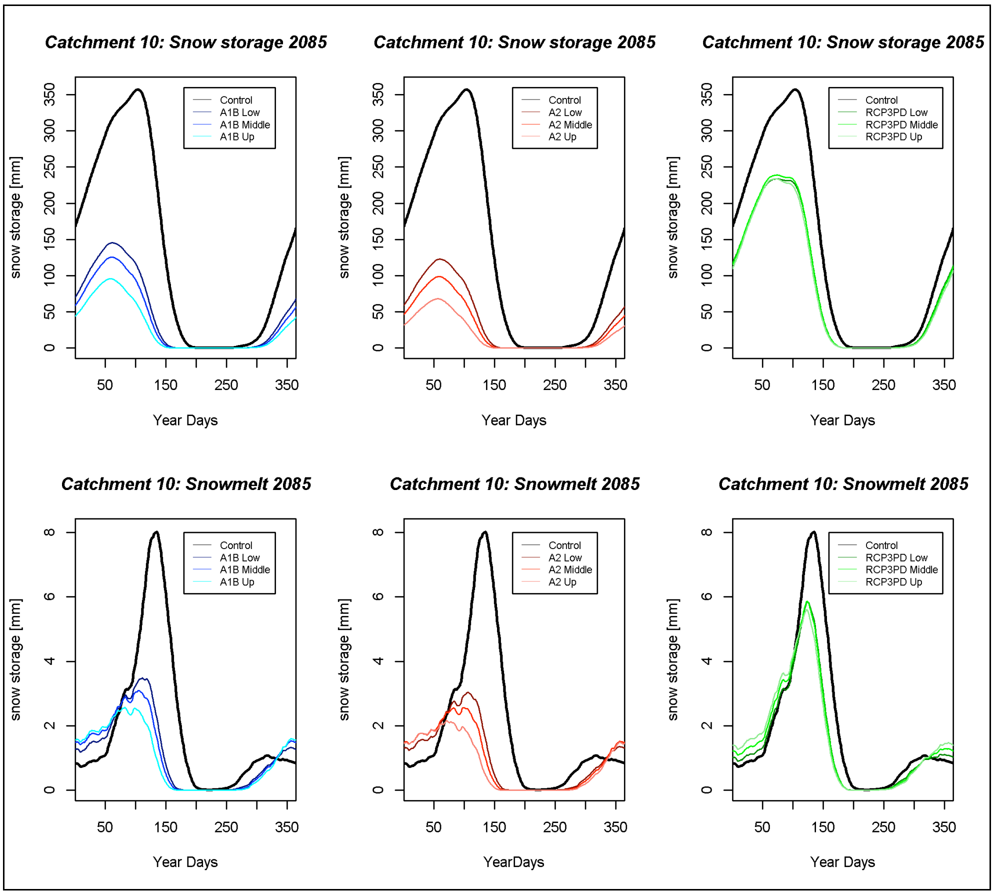


Figure 23: Thirty-year average simulated snow storage and snowmelt in catchment 10 for the period 2070 – 2099 and for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to control period (black)

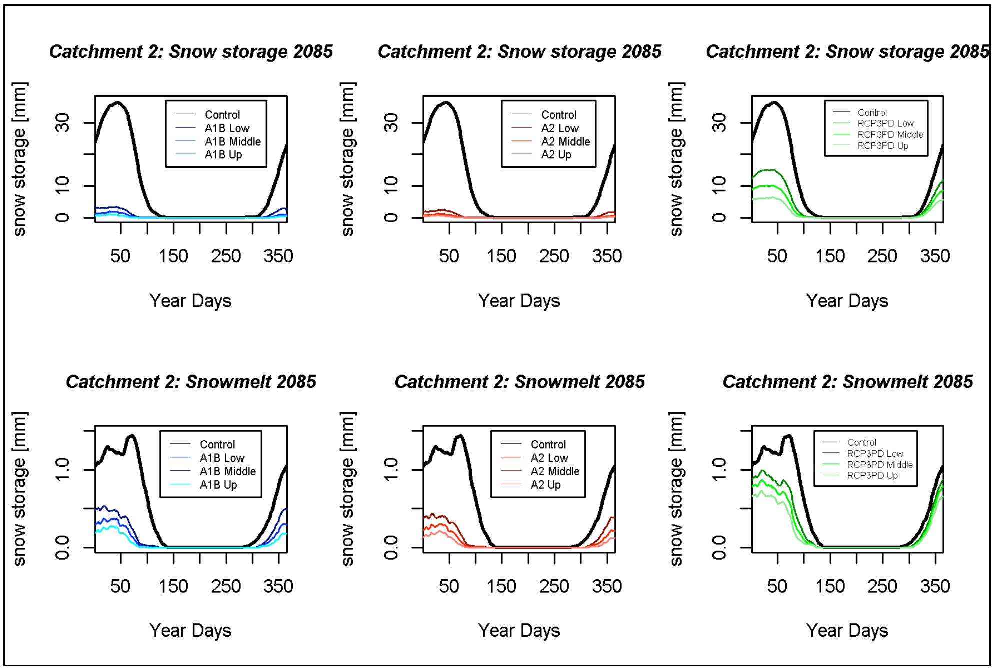


Figure 24: Thirty-year average simulated snow storage and snowmelt in catchment 2 for the period 2070 – 2099 and for emission scenario A1B (blue), A2 (red) and RCP3PD (green) with respect to control period (black)

There are some features common to all simulations in both catchments:

- Snow storage and the related snowmelt will diminish in both catchments independently of the emission scenario.
- Changes using emission scenario RCP3PD are smaller than for the other two scenarios A1B and A2. The two latter scenarios show similar decrease projections, with the A2-scenario simulating a slightly greater diminution.
- The snow-free period will become longer in all scenarios even if this period in scenario RCP3PD remains relatively stable. For the scenarios A1B and A2 the period without snow storage will begin earlier in spring and terminates later in autumn.

Even if a superficial look at figures 23 – 24 gives the impression that in catchment 2 there will be a larger impact than in catchment 11, because snow storage will almost disappear under emission scenarios A1B and A2. A more attentive look gives another picture of the situation.

First of all the scales of the two figures are not the same: in the catchment 11 there is a maximum snow storage of 357mm in the control period, whilst the maximum for catchment 2 is only 36 mm. Snow storage in catchment 2 almost disappears in scenario period 2085 under emission scenario A1B and A2 because the yearly mean temperature at present is already close to the melting point of snow. With the projected climate warming it will be unlikely that snow can be stored over longer periods of time in this location. The quantity of water from snowmelt is accordingly much smaller because precipitation will fall increasingly in liquid form.

Even if the percentage diminution is higher in catchment 2, the greater impact for hydropower production is expected in catchment 11, where the amount of snow is greater. For this reason, tables 8 – 10 show the projected changes in snow storage and snowmelt both in percental and absolute form for the three scenario periods and in all catchments.

Table 8: yearly percental (left-hand table) and absolute (right-hand table) diminution in snow storage for emission scenario A1B in all twelve catchments and all scenario periods

	Percentage diminution [%]				Diminution [mm/y]		
	2035	**2060**	**2085**		**2035**	**2060**	**2085**
1	57.9	83.5	91.8	**1**	-4720	-6806	-7485
2	71	91.6	96.1	**2**	-2359	-3044	-3193
3	34.1	56.5	68.4	**3**	-14271	-23640	-28587
4	47.3	73.8	85	**4**	-6701	-10456	-12036
5	39.4	63.9	75.7	**5**	-9510	-15412	-18264
6	32.1	54.6	66.3	**6**	-14082	-23990	-29105
7	36.2	59.7	71.7	**7**	-11973	-19762	-23739
8	25.2	45.5	56.5	**8**	-17439	-31430	-39022
9	33.4	56.8	68.4	**9**	-15075	-25620	-30860
10	35	59.3	71.2	**10**	-17163	-29089	-34938
11	30.1	52.9	64.8	**11**	-18548	-32561	-39925
12	37.1	61.6	73.7	**12**	-14389	-23899	-28593

Table 8 shows the projected diminution using emission scenario A1B. It is possible to see that in all catchments a diminution is projected in all scenario periods. The percentage diminution is greater for the southern catchments such as numbers 1 and 2 while the absolute diminution is greater in the northern catchments, where the amount of snow is much greater.

Table 9: yearly percental (left-hand table) and absolute (right-hand table) diminution in snow storage for emission scenario A2 in all twelve catchments and all scenario periods

	Percentage diminution [%]				Diminution [mm/y]		
	2035	**2060**	**2085**		**2035**	**2060**	**2085**
1	53.1	82.7	95.1	**1**	-4333	-6744	-7757
2	66.3	91.1	97.7	**2**	-2202	-3028	-3246
3	30.8	55.6	75.4	**3**	-12860	-23255	-31510
4	43	72.9	90.4	**4**	-6090	-10324	-12807
5	35.6	62.9	82.3	**5**	-8582	-15181	-19853
6	28.8	53.7	73.5	**6**	-12646	-23583	-32256
7	32.6	58.8	78.7	**7**	-10777	-19447	-26030
8	22.5	44.6	64	**8**	-15557	-30825	-44200
9	30	55.9	75.4	**9**	-13533	-25194	-34021
10	31.4	58.3	78.3	**10**	-15406	-28611	-38405
11	26.9	51.9	72.3	**11**	-16573	-31972	-44513
12	33.4	60.6	80.6	**12**	-12963	-24526	-31264

The simulations obtained using emission scenario A2 (table 9) are very similar to the simulations obtained using emission scenario A1B. The patterns are the same. In scenario period 2070 – 2099 the diminution is greater than with emission scenario A1B.

Table 10: yearly percental (left-hand table) and absolute (right-hand table) diminution in snow storage for emission scenario RCP3PD in all twelve catchments and all scenario periods

Percentage diminution [%]

	2035	2060	2085
1	55.6	62.3	59.2
2	68.7	74.9	72.1
3	32.5	36.9	34.9
4	45.2	51.2	48.2
5	37.5	42.5	39.9
6	30.5	35.1	32.7
7	34.4	39.1	36.7
8	23.9	27.9	25.6
9	31.8	36.6	34.1
10	33.2	38.4	35.8
11	28.6	33.1	30.7
12	35.3	40.6	38.1

Diminution [mm/y]

	2035	2060	2085
1	-4530	-5077	-4826
2	-2283	-2491	-2396
3	-13590	-15449	-14588
4	-6400	-7254	-6833
5	-9058	-10253	-9626
6	-13384	-15410	-14371
7	-11393	-12936	-12154
8	-16520	-19319	-17717
9	-14325	-16508	-15382
10	-16307	-18811	-17532
11	-17589	-20359	-18901
12	-13697	-15733	-14780

Emission scenario RPC3PD (table 10) causes the smallest diminution in snow storage and in snowmelt, but even with this scenario the diminution is significant in all catchments.

Comparing the different emission scenarios, it is possible to see that in the period 2021 – 2050 emission scenario A1B has a greater impact than emission scenario A2. The difference between the two emission scenarios becomes gradually smaller, and after scenario period 2060 the biggest diminution in snow storage and snowmelt is generated using emission scenario A2.

Emission scenario RCP3PD shows a slightly different pattern in the evolution of the simulations: the diminution increases from scenario period 2035 to scenario period 2060, but decreases again in scenario period 2085.

These findings are consistent with the definition of the different scenarios. Simulations with emission scenario A1B cause initially the biggest diminution because in this scenario there is very rapid economic growth, which also determines a rapid increase in greenhouse gas emissions before new technologies can successfully be introduced. Emission scenario A2 predicts a moderate growth that is maintained until the end of the century. This is the case because in scenario period 2085, the effects on snow storage and snowmelt are bigger using this scenario with respect to the scenario A1B. Emission scenario RCP3PD is designed for a world that succeeds in limiting warming to 2°C. The projected diminution in snow storage and snowmelt until scenario period 2060 is the result of present emissions. The successful measures to limit greenhouse gas emissions are responsible for the later stabilisation in snow cover and snowmelt.

Returning to the two previous examples, table 8 shows for emission scenario A1B that snow storage diminishes in percentage more strongly in catchment 2 than in catchment 11 (e.g. 96.1% vs. 71.2% for the emission scenario A1B and scenario period 2085). Consistently, snowmelt also diminishes more strongly in the southern catchment, albeit less dramatically (e.g. 80.2% vs. 44.3%).

In absolute terms however, a diminution of 96.1% of snow storage in catchment 2 means a diminution of 3193 mm/a, while a diminution of 71.2% in catchment 11 means a diminution of 34'938 mm/a. For hydropower energy production the losses in snow storage in the northern catchment are quantitatively much more significant than in the southern one.

In summary, it is very likely that the projected changes in snowmelt will affect the operation of both sites. Missing snowmelt in spring will affect the period of reservoir filling in both catchments. This means that the filling of the reservoir will probably have to begin earlier, and even then it is questionable if the reservoir can be filled to the same levels as the present day. The implications of the diminution of snow storage for hydropower plants are significant. The operators will have to adapt their management strategies to incorporate a shift of the snowmelt season earlier in spring, less water coming from snowmelt in this season, and much more precipitation falling in liquid form.

Impacts on energy production

Going back to simulated runoff changes, it is interesting to investigate what these changes mean in terms of changes in energy production. This aspect can be analysed using the gross hydropower potential (GP) as Lehner et al. (2003) did. The formula used in Lehner et al. (2003) is a simple formula to find the potential energy $m \cdot g \cdot h$. His definition of gross hydropower potential is "the annual energy that is potentially available if all natural runoff at all locations was to be harnessed down to the sea level (or to the border line of a country) without any energy losses" (Lehner et al. 2003). In this thesis the formula was adapted according to Gaudard and Romerio (2013) and their definition for computing the theoretical changes in power generation:

$$P = \delta \cdot \Delta Q \cdot g \cdot \Delta h \qquad \text{[W]}$$

where P is the power, δ is the water density [Kg/m^3], ΔQ is the difference in runoff between the control period and the simulated future scenario [m^3/s*]*, *g* is the gravitational acceleration [m/s^2], and Δh is the drop height of the water [m]. The required data on drop height in different power plants for this calculation are not always publicly available. Some operators make them public via the internet, whilst others do not. For this reason this evaluation is limited to two catchments, where data on drop height were available: catchments 11 and 1. The drop height in catchment 11 is 850 meters, whereas the drop height in catchment 1 is 235 meters. The projected diminutions in power production are resumed in table 11, still using the most probable diminutions in runoff of the middle quantile's simulations:

Table 11: Absolute (upper tables in MW) and percental (lower tables) diminution in power production with respect to the control period in catchments 11 and 1 for all emission scenarios and all scenario periods

Absolute diminution catchm. 11 [MW]

	A1B	A2	RCP3PD
2035	6048	5259	5522
2060	20511	19985	12096
2085	29715	34711	12885

Absolute diminution catchm. 1 [MW]

	A1B	A2	RCP3PD
2035	2108	1890	1963
2060	6398	6252	3853
2085	9669	11123	4289

Percentage diminution catchm. 11 [%]

	A1B	A2	RCP3PD
2035	3.9	3.39	3.56
2060	13.2	12.9	7.8
2085	19.8	22.4	8.3

Percentage diminution catchm. 1 [%]

	A1B	A2	RCP3PD
2035	13.3	12	12.4
2060	40.5	39.6	24.4
2085	61.1	70.4	27.1

For the calculation of the percental diminution in power production, the absolute losses were related to the current yearly production specified by the plant operator (catchment 11 = 155 GWh, catchment 2 = 15.8 GWh). The resulting diminutions (table 11) show that the impact of climate change will be greater in catchment 1. This fact reflects the projected diminutions in total runoff that are more significant than for catchment 11. Moreover, the percental diminution in catchment 1 is more relevant because the current power production is much smaller than in catchment 11. The projected diminution by the end of century in the worst case is 22.4% for catchment 11 and up to 70.4% for catchment 1!

The difference in the projected diminution can be explained by the projected drastic diminution of snow storage and snowmelt and the diminution of runoff. This would mean that the difference in diminution between catchment 1 and catchment 11 would apply to other southern (respectively northern) catchments according to the differences in climatological data.

These results do not account for energy losses arising from the turbine. If one wants to allow for these losses it is necessary to introduce another factor. The efficiency of a turbine lies between 75% and 85% (Evans et al. 2012) depending on the type of the turbine: reaction turbines (Francis) have a better efficiency than impulse turbines (Pelton) (Gaudard and Romerio 2013). Therefore it would be possible to change the formula into:

$$P = \eta \cdot \delta \cdot \Delta Q \cdot g \cdot \Delta h \quad [\mathrm{W}]$$

where η is the efficiency of the turbine (or turbines) used in the power plant. In this thesis this will not be performed due to the lack of precise information (e.g. the exact efficiency in a specific power plant, the presence of different groups of turbines in the same site and the current condition of the different turbines).

6. Minimizing the impacts for energy production

The results of the different projections indicate that it is very likely that runoff will diminish in all catchments and in all scenario periods, independently of the emission scenario used. Tables 8, 9 and 10 already showed the exactly percentage of these forecast diminutions in runoff for each catchment. This section will approach the second question formulated in the introduction of this master's thesis:

How is it possible to minimise the impact of these changes in order to optimise energy production?

To answer this question in a clear and simple way only the most probable simulations (M-Quartiles) and only one emission scenario (A2) will be considered. Scenario A2 was chosen for following reasons:

- The correlation of economic growth and energy consumption has been investigated in several studies for both industrialised and developing countries (Hwang and Yoo 2012, Hua and Huai-Shu 2013, Alkhathlan and Javid 2013, Huayong and Han 2014, Wang K.-M. 2013). It is generally accepted that a growing economy creates a higher energy demand.
- The introduction of new technologies to mitigate greenhouse gas emissions is a long-term prospect, even in developed countries. Moreover, there are regions around the world, where these technologies are not available or are too expensive, and other regions that do not yet have the economical interest to introduce them.

The last findings of the IPCC (2014) on greenhouse emissions also support the choice of the A2 emission scenario and can maybe be interpreted on the basis of all these points: "A new report by the Intergovernmental Panel on Climate Change (IPCC 2014) shows that global emissions of greenhouse gases have risen to unprecedented levels despite a growing number of policies to reduce climate change. Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades" (IPCC 2014).

Table 9 resumes the projected diminutions in runoff for all observed catchments under emission scenario A2. The projected mean diminutions in runoff over all catchments are 2% by scenario period 2035, 6.9% (2060) and 12.1% (2085). Even if Hänggi and Weingartner (2012) found that "changes in hydrological conditions do not necessarily translate one to one into changes in hydropower production", it is highly probable that in the future the energy production of hydroelectric power stations in Ticino will be quantitatively lower than at present. There are different possibilities to minimise at least the economical impact of these losses in production:

a) Changing the filling period of the reservoir

Gaudard et al. (2013) suggest anticipating the maximum volume of stored water from August to July in their analysed Toce basin. They also suggest a more rapid emptying of the reservoir in summer beacuse the reservoir can be filled already in autumn due to the projected augmention in precipitation and runoff in this season (Gaudard et al. 2013).

Because the analysed catchments in this master's thesis are situated in the Southern Alps (like the Toce basin), presumably this suggestion can also apply to them. It has however to be remembered that variations even between adjacent catchments can be significant.

b) Changing period of electricity production

Gaudard et al. (2013) point out that "the production will likely increase in winter as a result of projected price dynamics." They further investigate the impact of climate change on energy consumption and consequently on market prices analysing "Heating Degree Days" (HDD) and "Cooling Degree Days" (CDD). This is a method to measure the demand for energy needed to heat/cool a building respectively. Gaudard et al. (2013) conclude that "the impact of climate change on consumption is likely to be negligible". The same conclusion is supported by CH2014 (2014). For this study the already small decrease in energy consumption due to climate warming (decreasing HDD) is further reduced by a "rebound effect". This effect describes an increased consumption as a consequence of improved energy efficiency. A direct rebound effect applies to the same machine (e.g. a new television is more efficient and as consequence is employed more frequently). An indirect rebound effect concern different services (e.g. if one can save money because of a more efficient new machine, this money can be spent in other energy-intensive services). A practical example is that "households heat relatively more when the same room temperature can be obtained at lower cost." (CH2014, 2014). Therefore CH2014 (2014) found out that a theoretical decrease in consumption of 7.25% would lead to a decrease in energy consumption of only 0.5%.

The price dynamics mentioned previously can be understood in part by observing other renewable energy sources, e.g. photovoltaic. This energy source is projected to increase in the future, and for this reason there will be more energy from photovoltaic sources in summer, which will modify market prices. In winter, energy production will diminish. This partially explains the projected price evolution.

For this reason it would be reasonable to shift the period of peak production of hydroelectric energy to the winter. There would be more water available for hydroelectric plants, and the revenues would be higher.

c) Shifting to pumped storage power plants

As already highlighted by Terrier et al. (2011) for the basin of Mauvoisin, in the future it could be economically profitable for some hydropower plants to install a pumped storage system. This technology allows the operator to produce energy more focused on peak hours, when energy demand and prices are economically more interesting. The economical efficiency of this system depends on the ratio between peak and off-peak prices (Gaudard and Romerio 2013). In order to optimise revenues, the capacity of the downstream reservoir (from which water is pumped into the upstream reservoir to be turbinated again) should be sufficiently large.

Another advantage of pumped storage power plants is that they can help regulate the energy grid. This already happens at present. The increasing energy production from wind, photovoltaic and other renewable energies let the volatility of supplied energy in the grid increase. For this reason, the regulative importance of hydropower plants in the future may increase, and pumped storage systems, with their capacity to produce energy when needed, will be very important players.

At present, only 4% of total produced electricity from hydropower plants comes from pumped storage plants (BFE 2013a). A development of this type of plants is suitable.

7. Conclusion

This master's thesis has focused on the influence of climate change on runoff in twelve catchments in the Ticino Canton and the consequences of these projected changes on hydro electrical energy production. The simulations have been carried out with the hydrological model PREVAH driven by climatological data from C2SM. The simulations were calculated for three scenario periods (2021 – 2050, 2045 – 2074 and 2070 – 2099) and three emission scenarios (A1B, A2 and RCP3PD).

At the beginning of this thesis two questions were formulated:

- Which changes will there be in the runoff regime of the selected catchments in the future?
- How is it possible to minimise the impact of these changes in order to optimise energy production?

The simulations provide a clear answer to the first question: the projections indicate a decrease in runoff for all catchments, independently of the emission scenario used, and over all scenario periods.

A first conclusion is therefore that runoff in the investigated catchments in the Ticino Canton will very likely diminish in the future. This first answer is reliable because simulations are based upon the sole influence of climate change, and are not influenced by anthropogenic variables such as changes in politics or discovery of new technologies. The methodology used in this study also accounts for uncertainties of the different global and regional circulation models, and reflects the best knowledge on hydrological-atmospheric issues at present. It is indeed true that this study does not account for parameter uncertainty, but as Schaefli (2005) emphasises: this factor plays a minor role in overall uncertainty.

The simulations show slight differences in yearly runoff between catchments in North and others in South Ticino. These differences are quantitatively not very significant but they can still reach about 3.7% of total runoff in scenario period 2070 – 2099.

A second conclusion concerns the role of snow in future periods. Snow cover, snow storage and consequently snowmelt will inexorably decrease over the years. Snow storage and snowmelt in the southern part of Ticino will almost disappear, but the most important consequences in absolute terms are expected in the northern catchments. These changes will have a considerable influence on the management of power plants, primarily due to the earlier beginning of the filling season, and further because of the reduced amount of snowmelt filling the reservoir.

A third conclusion is that, even if a change in runoff does not automatically mean the same amount of change in energy production, it is also very likely that energy production in Ticino for the analysed catchments will diminish in the future.

A simple calculation of losses in power production for the catchments 1 and 11 showed that for scenario period 2070 – 2099 there will be a significant diminution, especially in the southern catchments in Ticino.

The answer to the second question is more complicated. The approach to this question has been qualitative, because a quantitative study goes beyond the possibilities of this study. Nonetheless some points based mostly on other studies could be highlighted.

1) The filling period of the reservoir has to be adapted to the change in runoff distribution over the year.
2) The period of peak energy production should change in relation to the evolution of energy prices.
3) The construction of more pumped storage power plants will represent a major advantage for hydropower plants in the future energy market.

These three aspects represent possible ideas for further research that is needed in order to find solutions for the projected diminutions in runoff, and consequently for energy production in the future.

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Signature:

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