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Subject: Cover letter accompanying resubmission of Research article (MS No.: nhess-2019-359)

Dear Editor,

We hereby submit a revised manuscript for review for Natural Hazards and Earth System Sciences (NHESS). The paper was previously reviewed (nhess-2019-359) with a decision of major revision.

We have now revised the paper in accordance with the comments from the reviewers. The details of the changes are outlined in the responses to the reviewers included with the submission.

The main comments of the first reviewer are: the results, which use input from one climate model, should be given more context in regard to other climate scenarios and some key uncertainties should be better presented, and the climate change input data should be described in more detail. *To address the comments, we have compared in detail our study results with RCP8.5 (worst case scenarios) results of other studies, and other key uncertainties are also included in the discussion section of the revised manuscript. We have also described in detail the climate change input data in the revised manuscript (section 2.2).*

The main comments of the second reviewer are: To discuss and justify the use of only one RCM that was driven by bias-corrected input of only one GCM, to reduce the lengthy description of the hydrological model and the regionalization approach and to expand the description of the novel bias correction method in the method section of the paper. *To address the comments, we have discussed in detail the comparison of the single RCM-GCM results of our study with other studies in the discussion section of the revised manuscript, and we have justified the reasons for the use of a single RCM-GCM in the responses to the reviewers. We have also revised and shortened significantly (from 6 to 2.5 pages) the hydrological model and regionalization approach and expanded the novel bias correction method (from 0.5 to 2.5pages) in the method section of the revised manuscript (section 2.3 and section 2.2 respectively).*

We hope the major revision done in the paper could be suitable for NHESS.

Best Regards,

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Hydrological impacts of climate change on small ungauged catchments-results from a GCM-RCM-hydrological model chain

We would like to thank the reviewers for their thoughtful comments and efforts towards improving our manuscript, which have helped us to improve the quality of the manuscript. In the following, we give responses to the comments/concerns the reviewers raised.

Reviewer 1

General comment

In the manuscript the regionalized DDD model with dynamic river network was used to study climate change impacts on hydrology by 2070-2100 in ungauged catchments in the Bergen area in western Norway. Six ungauged small rural catchments are modeled with a single high-resolution downscaled climate scenario.

The manuscript is well structured and well written and bring new knowledge on estimation of climate change impacts on small ungauged basins with sub-daily time steps. However, to improve the manuscript, the results, which use input from one climate model, should be given more context in regard to other climate scenarios and some key uncertainties should be better presented.

General Answer

Thank you. To improve the manuscript, we have compared in detail our study results with RCP8.5 (worst case scenarios) results of other studies, and other key uncertainties are also included in the discussion section of the revised manuscript. We have also compared results of RCP8.5 and 4.5 of other studies.

Detailed comments

Comment on Abstract:

The abstract should clearly state the climate scenario (especially rcp) for which the results are based since this affects the likelihood of the proposed changes (ie. these are apparently with the rcp8.5 and are therefore likely to be the upper end of the proposed changes). The uncertainties due to use of only one climate scenario should be shortly acknowledged also in the abstract and the percentage changes of the results should be provided with less accuracy (ie. not well 256.3 % but with e.g. 260 %).

Answer

We have revised the abstract section of the manuscript accordingly. We have included the uncertainties due to use of only one climate scenario. The results are also provided with rounding to the nearest integer. The revision is found in the abstract, result and discussion sections of the revised manuscript. Tables, 5,7 and 9 containing decimals, are also rounded.

Comment on Data and methods:

More background information from the Bergen area floods and the mechanism (snow or rain or both) could be provided. In discussions the results could be reflected with this.

Answer

More background information on Bergen climatic conditions, floods, shifts in floods, and floods generation mechanisms are included in the revised version of the manuscript. The floods in the southern west part of Norway are mainly caused by rain in the autumn season.

Revised Manuscript

The included information is found in the data and methods section of the revised manuscript, lines (122 to 146).

Comment on Section 2.2:

Section 2.2 includes information of the climate change input data used. However, the climate change input data should be described in more detail. The climate scenario used should be more clearly stated (Global climate model, regional climate model, rcp) (NORESM-M, WSF, but the rcp is not mentioned here, apparently rcp8.5) – the corrections made to the data should be provided with more details. Is only the GCM corrected and for which variables? Is there any bias correction on the RCM data? How well do the temperatures and precipitation compare to observations? -the use of only one scenario just be better justified (since the common approach these days in to use several scenarios to enable uncertainties to be included). Why this particular model and why only one?

Answer

We have revised and rewritten section 2.2. The RCP used is 8.5, and the global climate model NorESM1-M (r1i1p1) output used as forcing data at the boundaries of WRF was bias corrected before the regional downscaling. We followed the approach of Bruyère et al. (2015) and corrected the monthly mean values towards the monthly mean of the reanalysis ERA-Interim (Dee et al. 2011). The correction was performed for the skin temperature and the three-dimensional pressure, humidity, temperature and the wind components. The bias correction method used is explained in detail in the data and methods section of the revised manuscript.

We agree that it is quite common to use ensembles of scenarios in climate impact studies; However, in the hydrological impact study of small catchments, the short response time of small catchments requires high temporal and spatial resolution (short duration and small special scale) climate data and getting such ensembles data is a challenge. To our knowledge, no other convective permitting, century-long, dynamically downscaled climate projections is available for

Norway for short duration rainfall with a small spatial scale so that a standard ensemble analysis is not possible.

Revised Manuscript

The included information is found in section 2.2 of the revised manuscript, lines (160 to 227).

Comment on Discussion:

Since only one climate scenario is used, the influence of this decision on the results should be discussed. Table 4 states the temperature and precipitation changes with the used climate scenario (the GCM-RCM and rcp of the scenario should be added to the table header) and on page 2 the range for rcp8.5 is stated. However, these should be compared more clearly in the discussion or elsewhere (how does the chosen scenario compare to others, is it e.g. wetter than average). Also, the range of temperature and precipitation with other rcps than just 8.5 should be provided for context. The results are currently only been compared to the rcp8.5 results of e.g. NCCS report, also some comparison with the rcp4.5 could be provided for more context. How does the use of only one scenario influence the results and what are the likely results with other scenarios (e.g. are these likely to be the top end of changes in floods which can be used as worst case scenario). Currently the results, which are stated with high accuracy, can provide false sense of certainty while this major uncertainty is not well established. (The emissions used in RCP8.5 pathway are nowadays considered by some scientists as rather unlikely due to the ongoing mitigation efforts and the sinking prices of renewables. Therefore, there has been arguments against the use of this scenario as a “business as usual” scenario).

The results showed large increase in flood risk due to climate change. Other studies are referred to but the main differences between these studies explaining the differences in the results (the inclusion of different types of catchments with more snow dominated flooding and the use of

several different climate scenarios) should be analyzed. The changes in max SWE (table 4) are very large, any comment on this? What is the influence of the snow model type used?

There is also big increase in evapotranspiration in the climate change scenario (table 4). What could explain this? And what is the influence of the relatively simple evaporation model, which is correlated to temperature and influenced by precipitation through soil moisture but does not use other input from the climate model such as changes in wind speed, cloudiness or humidity? The changes in evapotranspiration only have a limited effect the flood discharges, but the low discharges are more sensitive to these changes.

Answer

The header of table 4 has been revised accordingly i.e., the GCM, RCM and RCP are added. We have compared changes in precipitation, temperature and floods between our findings and the Norwegian Centre for Climate Services (NCCS) under Climate in Norway 2100 report (Hanssen-Bauer et al., 2015) with RCP8.5. WE have also compared the findings of the report with RCP8.5 and 4.5. The comparison has been done in the discussions section of the revised manuscript.

The comparisons of the precipitation and temperature changes with our climate model and the NCCS report with RCP8.5 show that our findings are colder and wetter than the NCCS report. The precipitation and temperature changes for Norway are 17% and 3.7°C for RCP8.5 at the end of the century (2071-2100) compared to the reference period (1971-2000). Our findings show that the mean annual changes are 22% and 3.3°C at the six study catchments in Bergen area at the end of the century compared to the reference period (1981-2011). The results are generally comparable with small differences.

Revised Manuscript

The included comparison is found in the discussion section (4.2.1) of the revised manuscript lines (456-464).

Detail comparisons of 200 years flood changes, between the Lawrence (2016) findings with RCP 8.5 and our findings, have been done in the revised version of the manuscript. The RCP8.5 results of the Lawrence (2016) report show slightly lower flood changes than our findings. Lawrence (2016) found that the increase in the 200 years flood is between 20% to 40% for seven of the ten study catchments used in the Hordaland county at the end of the century. Our study catchments are also located in the Hordaland county. The results of our study show that the 200-year flood changes range from 20% to 43% for five of the six the study catchments. The comparison shows that our findings are similar to the RCP8.5 report and likely at the top end of changes in floods which can be used as a worst-case scenario at the Bergen area. The slight differences in the findings are related to the temporal resolutions used (3hourly in our study and daily in the report), the bias correction methods used, the number of GCMs-RCMs used and the differences in the sizes of the catchments (less than 10km² in our study, and 6km² to 15499km² in the report).

Revised Manuscript

The included comparison is found in the discussion section (4.3.2) of the revised manuscript, lines (620-634).

We have explained the differences in our findings and Lawrence (2016) report related to changes in flood frequencies. The main differences are the number and types of climate models, RCPs, the bias correction method, the catchment sizes and the temporal resolution used in the study. However, the comparison location is the same. We have compared our findings with results from 10 catchments in the Hordaland county (where our study catchments are located) in the report.

Revised Manuscript

The included comparison is found in the discussion section (4.3.2) of the revised manuscript, lines (636 - 648).

The main reason for the very large increase of changes in maximum SWE is due to a real effect of warming temperature that shifts the rain/snow boundary higher up in elevation. The other reason *could be the limitations and uncertainty in estimating the snow model parameters. The snow model parameters in Distance Distribution Dynamics hydrological model are estimated from the nearby catchments which had been estimated from daily observed precipitation and temperature data in the Thomas Skaugen 2015 paper.*

The big changes in actual evapotranspiration tells us that in the future period there will be more water available (to evaporate) and higher temperature (to cause evaporation) than the reference period. Yes, we agree with the reviewer in that there is a limitation with the simple evaporation model since actual evaporation is not only affected by temperature but by additional climatological factors like wind speed, humidity, cloudiness etc. This limitation could also be the other reason for a big change of actual evapotranspiration between the reference (1981-2000) and future periods (1970-2100).

Revised Manuscript

The limitation related to the simple evaporation model is included in the revised manuscript, lines (656- 664).

4.4. Limitations RCPs should be added to GCMs and RCMS as source of uncertainty or limitation to the study.

Answer

We have included the limitations in the use of a single Representative Concentration Pathway (RCP8.5) in the revised manuscript.

Revised Manuscript

The included limitation is found in the limitation section (4.4) of the revised manuscript, lines (668-674).

Reviewer 2

This study aims at assessing the impacts of climate change on flow patterns and patterns and frequency of floods in small ungauged rural catchments in Norway. It is an interesting manuscript that is mainly well prepared and structured. The study reveals that higher mean annual discharges are expected at the end of the 21st century. Mean annual floods are projected to increase compared to the baseline period. The manuscript's results contribute to the knowledge of climate change impacts in terms of river discharges in western Norway.

Three Main comments/concerns:

1. Only one RCM has been used that was driven by bias-corrected input of only one GCM. Nowadays, a state-of-the-art climate impact study should not base its results solely on one climate simulation, but on an ensemble of climate model simulations. Moreover, the results are only discussed for RCP8.5 at the end of the 21st century. In the discussion section, the authors address this issue and put their results into a larger context (Norway study), which is important, but not done in sufficient detail. Plotting precipitation and temperature projections of the NorESM1-M / WRF model in the context of the CMIP5 or CORDEX ensemble would be helpful here. However, I am not sure whether putting the results into the context of another study justifies the approach of using only one climate simulation as input.

Answer

Since the new climate simulation is specially made for southwest coast of Norway with a time resolution of 3 hours and 4km by 4km spatial resolution, the comparison with other studies is interesting to see how the new method performs compared to what we know before and if it seems reasonable. Therefore, we believe that putting our results into the context of another study justifies the approach of using only one climate simulation as input.

We agree that the state-of-the-art of climate impact study normally is based on an ensemble of climate model simulations; however, for climate impact studies on small catchments, we have used only one GCM-RCM model simulations. We have used a single GCM-RCM model simulation is we actually can not find sub-daily data which is required for small catchments (< 10km²) study. We know that improvement is needed for the west coast of Norway so that we provide something brand new sub-daily climate data and bias corrected GCM data as input. The reasons for using a single GCM-RCM model simulation are summarized as follows:

- i) The single GCM-RCM simulation used in this study was generated based on the need to improve the precipitation distribution for the west coast of Norway, this was done through the new bias correction method and by utilizing kilometre-scale resolution.*
- ii) Limited computational resources to conduct ensembles of downscaling. This 60-year GCM-RCM downscaling alone has used approximately 650,000 cpu hours on a national hpc machine.*

We have discussed in detail the results obtained using a single scenario and single climate model into a larger context in the discussion section of the revised manuscript. The discussions are found on lines 445 to 483 and lines 620 to 648 in the discussion section.

2. The description of the hydrological model and the regionalization approach in the Method chapter is quite long (6 pages). I think, this is not appropriate for a manuscript claiming to

investigate climate impacts. In between I wondered whether the main focus of the manuscript is actually on climate impacts or on the methodology to be applied in ungauged catchments. What I would expect to read instead is something like this: "The DDD model is a lumped, conceptual hydrological model with a module simulating the slow flow component (subsurface) and the quick component (runoff dynamics)." Additionally, something about the temporal and spatial scales, it can be applied to, that it is not fully, or semi distributed...

Answer

Thank you. We have revised and shortened significantly (from 6 to 2.5 pages) the hydrological model and regionalization approach in the method section of the manuscript (section 2.3). We have included only the main points about DDD model and the regionalization methods.

Revised Manuscript

The revision is found in section 2.3 of the revised manuscript, lines (241 to 294).

3. Especially in the discussion and conclusion sections, the authors mention many times the novel bias correction method that has been applied. From my point of view, instead of providing a lengthy description of the hydrological model, a description of the novel bias correction method would be much more valuable in the context of a climate impact study.

Answer

Thank you. We have shortened the lengthy description of the hydrological model (from 6 pages to 2.5 pages) and expanded the novel bias correction method (from 0.5 page to 2.5pages) under section 2.3 and 2.2 respectively.

Revised Manuscript

The revisions are found in section 2.3 and section 2.2 respectively in the revised manuscript.

Besides these three main concerns I have made a lot of comments on the attached RC2-supplement-pdf file.

General comments

1. The introduction is a bit lengthy, particularly the section between rows 70-87.

Answer

The introduction is shortened. Particularly, section 70-87 is reduced significantly (from 70-87 to 71-82).

2. English is usually adequate, but some sentences are incomprehensible or poorly expressed, e.g. following sentence: "The regional impacts of climate change (e.g. on local flooding) come out with the necessity of orienting adaptation measures to local climatic, geographic, economic and social conditions."

Answer

We went through the manuscript and corrected the poorly expressed sentences.

3. The authors should consider having the manuscript revised by a native speaker.

Answer

We revised the language, and we believe that the language is enough for publication.

4. The authors use the term "hydroclimatic elements" meaning variables, such as precipitation and discharge. I recommend calling these "hydro-climatic variables" not elements.

Answer

Thank you. We have changed hydroclimatic elements to hydro-climatic variables in the revised manuscript.

Technical

1. Multiple citations should be ordered by year.

Answer

Thank you, we have revised accordingly.

2. Equations. Many variables in the equations are not explained or mentioned in the text, some examples: Eq.2: $Q(t)$; Eq.5: Cea ; Eq.6: M

Answer

We have explained the variables of the equations in the revised manuscript.

Following articles might be worth citing in some contexts in the manuscript.

- Blöschl, G. et al. (2019). Changing climate both increases and decreases European river floods. Nature
- Blöschl; G. et al (2017). Changing climate shifts timing of European floods. Science, 357, 588-590 C3

Answer

Thank you. We have included the references in the introduction (lines 45-47), study area (lines 143-146) and discussion (lines 554-556) sections of the revised manuscript.

Hydrological impacts of climate change on small ungauged catchments- results from a GCM-RCM-hydrologic model chain

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Abstract. Climate change is one of the greatest threats to the World's environment. In Norway,
a change in climate will strongly affect the pattern, frequency and magnitudes of stream flows.
However, it is highly challenging to quantify to what extent the change in climate will affect flow
patterns and floods from small rural catchments due to unavailability or inadequacy of hydro-
15 meteorological data for the calibration of hydrological models and tailoring methods to a small-
scale level. To provide meaningful climate impact studies at small catchments, it is therefore
beneficial to use high spatial and temporal resolution climate projections as input to a high-
resolution hydrological model. Here, we use such a model chain to assess the impacts of climate
change on flow patterns and frequency of floods in small ungauged rural catchments in western
20 Norway. We use a new high-resolution regional climate projection, with improved performance
regarding to the precipitation distribution, and a regionalized hydrological model (Distance
Distribution Dynamics) between the reference (1981-2011) and future (2070-2100) periods. **The
flow-duration curves of all study catchments show more wet periods in the future than during the
reference period. The results also show that in the future period, the mean annual flow increases
25 by 16% to 33%. The mean annual maximum floods increase by 29% to 38%, and floods of 2 to**

200 years return periods increase by 16% to 43%. The results are based on the RCP8.5 emission scenario from a single climate model simulation tailored to western Norway and the Bergen region and the results should be interpreted in this context. The results should therefore be seen in consideration of other scenarios for the region to address the uncertainty. Nevertheless, the study increases our knowledge and understanding on the hydrological impacts of climate change on small catchments at the Bergen area in the western part of Norway.

1 Introduction

Climate change is one of the greatest threats to human existence, economic activity, ecosystems and civil infrastructures (Kim and Choi, 2012). The climate change risks depend on: the magnitude of warming, rate of warming, geographic location, levels of development, vulnerability, and on the choices and implementation of adaptation and mitigation options (IPCC, 2018). The trends of changes in different parts of Europe vary considerably because of changes in large-scale atmospheric circulation or local orographic circulation (Eisenreich et al., 2005, Hattermann et al., 2007).

Changes in temperature and precipitation and the shift in winter precipitation from snow to rain will be crucial in studying impacts of climate change on hydrology of a catchment. These changes influence the hydrological regime of a stream, and the most serious and widespread potential impact of the changes is flooding (Baltas, 2007, Richardson, 2002, Thornes, 2001). The Blöschl et al. (2019) study shows that increasing autumn and winter rainfall resulted in increasing floods in Northern Europe. In Norway, the average annual temperature and precipitation are expected to

increase by 3.8 °C to 6.2 °C and 7% to 27% respectively by the end of the century using RCP8.5 emission scenario (Hanssen-Bauer et al., 2015). The largest increases in precipitation are mostly
50 expected during the autumn and winter months and will in turn impact the magnitude and in some cases the seasonality of peak runoff and floods. A climate impact study at Sogn and Fjordane county of Norway shows that flood peaks shift from summer to autumn for the future scenario (Chernet et al., 2014), and Donnelly et al. (2017) studied climate change impacts on European hydrology and found that in the Norwegian region, climate change will strongly affect
55 the hydrological cycle in the future period. Outside Norway, authors have reported that the frequency and magnitude of flows are being affected by the changes in climatic conditions (Alfieri et al., 2015; Madsen et al., 2014; Mallakpour & Villarini, 2015; Rojas et al., 2013). Climate change adverse results upon streamflow regimes worldwide (Pumo et al., 2016), calls for attention of the impact study on a local scale.

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Projected increase in the frequency and intensity of heavy localized precipitation events, based on climate models, contributes to increasing in precipitation-generated local flooding, and an increase in local sudden flooding is causing significant danger and loss of life and property (Borga et al., 2011, Kundzewicz et al., 2014). Local sudden floods (flash floods) usually occur in small
65 catchments (e.g., catchments less than 100 – 1000 km²). This type of flood event is usually short in duration, but it is usually connected with severe damage (Menzel et al., 2006). Studies show that the probability and magnitude of hazardous heavy precipitation events have been increasing in several European regions e.g., (Golz et al., 2016). Heavy localized precipitation could be caused by low pressure systems (e.g., western Norway (Azad and Sorteberg, 2017)) or because of
70 prevailing convective precipitation at hilly or mountainous areas.

A quantitative analysis of the impacts of climate change on flooding conditions requires simulations in a climatological-hydrological system. The models on which the simulations are based should give an adequate representation of the system dynamics relevant for different types of flow (e.g. floods) generation (Menzel et al., 2006). Hydrological models provide the means to conceptualize and investigate the relationship between climate (e.g. precipitation and temperature) and water resources (e.g. low flows and floods) of a region to assess the likely effects of climate change and propose appropriate adaptation strategies (Baltas, 2007). The results of regional climate impact studies help in proposing adaptation measures to local climatic, geographic, economic and social conditions (Hattermann, 2009, Krysanova et al., 2008). Hydrological impact of climate change is generally performed by following a sequence of steps from global and regional climate modelling, through data tailoring (downscaling and bias-adjustment) and hydrological modelling (Olsson et al., 2016).

Climate impact assessment on hydrology of small ungauged catchments using continuous hydrological modelling is challenging because of unavailability or inadequacy of hydro-meteorological data for calibration of hydrological models, short response time of the catchments, difficulty in describing local hydrological processes and coarse resolution of climate models. The challenge in coarse spatial resolution of climate models is due to poor representation of precipitation which is inadequate for assessment of impacts on smaller catchments (Quintero et al., 2018). For example, Pontoppidan et al. (2017) showed that during a flooding event in western Norway, the regional model simulated observed rainfall considerably better with a grid spacing of 3 km compared to a grid spacing of 9 km due to the complex terrain in the area. Therefore, to provide a meaningful climate impact result at small catchments, it is necessary to use high spatial

and temporal resolutions of projected climate data as forcing in high resolution hydrological
95 models (Lespinas et al., 2014; López-Moreno et al., 2013; Reynolds et al., 2015; Tofiq & Guven,
2014). Current efforts of coordinated regional downscaling in Europe (EURO-CORDEX e.g.
(Jacob et al., 2014; Kotlarski et al., 2014)) are performed on a 0.11° grid, however a new high-
resolution regional downscaling with improved representation of local precipitation distribution
for southern Norway is available (Pontoppidan et al., 2018), but has yet to be included in a full
100 hydrological model chain.

To solve the challenge related to lack of availability of a properly calibrated high-resolution
hydrological model at ungauged small rural catchments in Norway, a predictive tool has been
developed and tested. Tsegaw et al. (2019a) calibrated and validated Distance Distribution
105 Dynamics (DDD) hydrological model at forty-one gauged small rural catchments in Norway with
hourly temporal resolution. For predicting flow at ungauged catchments, the DDD model
parameters have been regionalized using three methods of regionalization (multiple regression,
physical similarity and combined method) and the methods have been tested on seven independent
catchments. The finding shows that the combined method performs the best of all the methods in
110 predicating flow. Even if the DDD model predicts flow at ungauged catchments satisfactory (0.5
 \leq Kling-Gupta Efficiency < 0.75), the model underestimates most of the observed flood peaks. To
improve the prediction of observed floods, a dynamic river network method has been introduced
and implemented in DDD (Tsegaw et al., 2019b). This improved setup has been used in this study
where the general objective is to assess the hydrological impacts of climate change on small
115 ungauged catchments using a novel model chain consisting of a high resolution, bias corrected
dynamical downscaled climate scenario and the improved DDD model. We specifically focus on:

- i. Assessing the impacts of climate change on the changes of flow patterns at ungauged small rural catchments around Bergen, Norway.
- ii. Assessing impacts of climate change on the pattern and frequency of floods in ungauged small rural catchments around Bergen, Norway.

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2 Data and methods

2.1 Study area

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The Bergen area is known for its wet climate. The location is in the south western Norway (60N,5E) and coastal climate and pronounced topography. For the normal period of 1961-1990, statistical reports show an annual precipitation of 2250 mm (Florida weather station) and typically precipitation occurs 243 days every year (i.e. days with 0.1 mm or more precipitation) (Kristvik and Riisnes, 2015). The region is mostly affected by orographic precipitation, which is produced when humid air from the Northern Sea is lifted as it moves over the mountain range. The air rises and cools, forming clouds that typically precipitates upwind of the mountain ridge. Particularly, prominent mountains oriented across the wind gradient receive the heaviest precipitation. This causes major variations in precipitation loads, even within small distances (Kristvik and Riisnes, 2015).

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Floods in south western part of Norway (where Bergen is located) are mainly caused by heavy rainfall during the autumn season (Roald, 2008). The Norwegian Center for Climate Services report (Climate in Norway 2100) pointed out that in river systems, dominated by rain floods, the magnitude of floods is projected to increase by almost 60% (RCP8.5) towards the end of the century, and more frequent and stronger intense rainfall events may in the future give special challenges in small, steep rivers which receive their flows from small catchments (Hanssen-Bauer et al., 2015). Vormoor et al (2015) found that autumn/winter events become more frequent by

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2099, which leads to an intensification of the current autumn/winter flood regime for the coastal catchments in Norway. Blöschl et al. (2017) studied the impacts of climate change on shifting the timing of European floods using observed floods and found that in the south western part of Norway, 50% of the stations show a shift towards later floods (at the end of a year) by more than +8 days per 50 years.

Six ungauged small rural catchments, located in western Norway around Bergen city, are used in this study. The catchments characteristics data are taken from <http://nevina.nve.no/> and <http://www.statenskartverk.no/>. The definition of small rural catchments is based on the report of Fleig and Wilson (2013) with an upper area limit of 50km². The catchments are selected for the impact study because there are critical infrastructures (e.g. culverts, bridges and buildings) at the outlet of the catchments which could be damaged by floods in the future period. We selected three catchments with bare mountain dominated (>50%) and three catchments with forest dominated (>50%) land uses to include diverse land uses in the study. The locations and observed river networks of the selected catchments are depicted in Fig. 1. The catchment descriptors (CDs) and outlet coordinates of each study catchment are presented in Table 1.

2.2 Climate, topography and land use data

2.2.1 Climate data and bias correction

The precipitation and temperature data used to drive the hydrological model are obtained from a simulation performed by the Weather Research and Forecasting model (WRF) version 3.8.1 (Skamarock et al., 2008). The model is non-hydrostatic and widely used for weather forecasting and research purposes. This RCP 8.5 scenario climate projection is unique because of its high

165 spatial grid resolution of 4 km x 4 km. To our knowledge, no other convective permitting, century-
long, dynamically downscaled climate projection is available for Norway. Precipitation and
temperature variables are available every 3 hours. However, regional models, as WRF, inherit
biases from the boundary conditions used to drive the model. These biases may lead to
misrepresentation of important features in the models, e.g. the known bias of the North Atlantic
170 storm track (Zappa et al., 2013) leads individual storms into central Europe instead of a more
northern path along the Norwegian coast as observations suggest. Therefore, the global climate
model NorESM1-M (r1i1p1) used as forcing data at the boundaries in WRF was bias corrected
before the regional downscaling. We followed the approach of Bruyère et al. (2015) and corrected
the monthly mean values towards the monthly mean of the reanalysis ERA-Interim (Dee et al.,
175 2011). The correction was performed for the skin temperature and the three-dimensional pressure,
humidity, temperature and the wind components. The correction of the driving fields led to a more
realistic representation of the North Atlantic storm track and the precipitation distribution in the
regional model simulation (Pontoppidan et al., 2018).

180 Bias correction is an often-used method to address systematic model errors. Many studies apply a
correction towards observation on variables as temperature and precipitation via a choice of
distribution mapping towards observations. Normally this is performed on the regional climate
model output (e.g. Muerth et al., 2013; Trambly et al., 2013). Such posterior bias correction highly
constrain the model output and the use of such have been questioned (Maraun, 2016; Maraun et
185 al., 2017). Correcting variables individually may violate physical consistency because it tampers
with known physical dependencies. Alternatively, bias correction can be applied upstream, i.e. on
the global climate model before it is used as driving data for a regional model. In principle, this

will allow the interior of the regional model to adjust to any physical inconsistencies applied at the boundaries and develop a physical consistent climate within the model domain. Such an approach is widely used in a “storyline” approach where one add a climate change signal to reanalysis data before the downscaling (e.g. Rasmussen et al., 2011; Schär et al., 1996). However this pseudo global warming method also have caveats; it assumes that the climate variability is stationary in time, an assumption which have been widely questioned (Christensen et al., 2008; Maraun, 2012; Vannitsem, 2011). Instead we use a method that corrects the global climate model’s monthly mean towards the reanalysis monthly mean. By doing so we overcome the stationary assumption because we retain the variability from the global model instead of limiting the variability to the reanalysis.

We bias corrected the global climate model driving data prior to the dynamical downscaling, leading to physical consistency in the interior domain, and a potential gain from the increased horizontal resolution. The approach showed improved precipitation representation in Australia (Rocheta et al., 2017), in North American climate (Wang & Kotamarthi, 2015; Xu & Yang, 2012, 2015) and in hurricane representation along the US east coast (Bruyère et al., 2014). In Norway the upstream bias correction led to a better represented North Atlantic storm track and an improved spatial precipitation distribution (Pontoppidan et al., 2018).

Mathematically the bias correction was performed following the anomaly approach (Bruyere et al., 2015). The reference period was selected to be a 30-year period from 1981 to 2010 and we adjusted the monthly NorESM1-M mean towards the monthly ERA-Interim (Dee et al., 2011) mean. For the reference period the 6-hourly NorESM1-M input data were split into a monthly

210 mean term and the deviation from this. For the future period the 6-hourly NorESM1-M input data were split into the monthly mean from the reference period and the deviation from this, leaving the climate change signal and the non-stationary variability in the deviation term. The new bias-corrected NorESM1-M data were then calculated by adding the monthly mean from the reanalysis product and the GCM deviation term. As opposed to the pseudo global warming method this
215 approach ensured that the experiment retained the variability of the driving climate model. The bias correction equations are as follows:

$$ERAI_{ref} = ERAI_{ref} + ERAI' \quad (1)$$

$$GCM = GCM_{ref} + GCM' \quad (2)$$

$$GCM_{BC} = ERAI_{ref} + GCM' \quad (3)$$

220 where the mean terms are from the 30-year reference period and the deviation is the deviation from the reference period mean.

Bruyere et al. (2014) investigated the effect of bias correcting single and multiple variables. The conclusion was that the best results were obtained when a multivariate bias correction was
225 performed. Therefore, we bias corrected the three-dimensional wind components, the temperature, the relative humidity, and the pressure fields in addition to the two-dimensional sea surface temperature fields in our driving data.

230

2.2.2 Topographical and land use data

The DDD model parameters, which do not need regionalization, are derived from an analysis of topographical and land use data of a catchment using GIS. The source of the topography and land use data is the Norwegian Mapping Authority (<http://www.statenskartverk.no/>). The 10m x 10 m DEM, the river network and the 1: 50 000 scale land use data have been retrieved and used in the study. The DEM has been re-conditioned to the naturally occurring river network using the Arc-hydro tool to create a hydrologically correct terrain model that can improve the accuracy of watershed modeling (Li, 2014). The re-conditioned DEM is further used to determine the distance distributions of hill slopes and river networks as needed by DDD.

240

2.3 DDD hydrological model

2.3.1 General description of the model

The Distance Distribution Dynamics (DDD) hydrological model is developed by Skaugen and Onof (2014) and currently runs operationally with daily and 3-hourly time steps at the Norwegian flood forecasting service. The model is semi-distributed conceptual and applicable for catchments ranging from small to large and temporal resolutions ranging from low to high. It has two main modules: the subsurface and the dynamics of runoff. The volume capacity of the subsurface water reservoir is shared between a saturated zone and an unsaturated zone. The volume of the saturated zone and the unsaturated zone are inversely related i.e. the higher the unsaturated zone volume, the lower the saturated zone (Skaugen and Mengistu, 2016, Skaugen and Onof, 2014). The dynamics of runoff in DDD has been derived from the catchment topography using a GIS combined with runoff recession analysis. In DDD, the distribution of distances between points in the catchment and their nearest river reach (distance distributions of a hillslope) is the basis for

250

describing the flow dynamics of the hillslope. The distribution of distances between points in the
255 river network and the outlet forms the basis for describing the flow dynamics of the river network.
The hillslope and river flow dynamics of DDD are described by unit hydrographs (UHs) which
are derived from distance distributions and celerity using a GIS and recession analysis respectively
(Skaugen and Mengistu, 2016, Skaugen and Onof, 2014). Figure 2 shows the structure of the DDD
model.

260 2.3.2 Dynamic river network method in DDD

Dynamic river networks and hence dynamic overland unit hydrographs are introduced and
implemented in the DDD model to improve the simulation of floods (Tsegaw et al., 2019b). The
mean of the distribution of distances from a point in the catchment to the nearest river reach (D_m)
becomes dynamic in the dynamic river network method. Therefore, we need to estimate the
265 dynamic D_m from the relation between upstream critical supporting area (A_c) i.e. the area needed
to initiate and maintain streams and D_m using GIS and python script as shown in Eq.(4). The
coefficients (a and b) are estimated for each study catchments and presented in Table 2. The
calibration parameter of the dynamic river network routine in DDD is critical flux (F_c) and is
estimated by regional regression in this study.

$$270 \quad D_m = aA_c^b \quad (4)$$

275 2.3.3 Model parameters and regionalization

The DDD model parameters are divided into three main groups. The first group are those estimated
275 by recession analysis from observed flow data (for gauged catchments) or through regionalization
for ungauged catchments (appendix 1), the second group are those estimated by model calibration

(for gauged catchments) against observed discharge or by regionalization methods (for ungauged catchments) (appendix 2), and the third group are those estimated from digitized geographic maps using a GIS (appendix 3). The snow routine in DDD has two parameters estimated from the spatial distribution of observed precipitation data (Skaugen and Weltzien, 2016). The shape parameter (a0) and the decorrelation length (d) of the gamma distribution of snow and snow water equivalent (SWE) are estimated from a previous calibration for 84 catchments in Norway (Skaugen et al., 2015). Since our study focuses on ungauged catchments, we cannot conduct calibration and recession analysis; therefore, we derived the model parameters needing calibration and recession analysis through combined method of regionalization using 41 gauged small rural catchments in Norway as a base (Tsegaw et al., 2019a). To estimate the regionalized parameters for this study (3 hourly time step), we have used the combined method of regionalization which has been recommended for estimating regionalized DDD model parameters with hourly resolution (Tsegaw et al., 2019a). In the combined method of regionalization, we have estimated the recession parameters and critical flux using multiple regression between model parameters and CDs, and the other parameters (all in appendix 2) using the physical similarity method with pooled donor catchments. The parameters of the model needing regionalization are shown in appendix 1 and 2 (the bottom 5 parameters in appendix 1 and all in appendix 2). The CDs of the study catchments, used for multiple regression, are presented in Table 1.

295

2.4 Impact study

We have extracted the precipitation and temperature data from the 4 X 4 km and 3 hourly resolution climate model. The climate data are forced into the DDD model to simulate the runoff, actual evapotranspiration and snow water equivalent (SWE) both for the reference and future

300 periods. We have used 30 hydrological years (1st of September to 31st of August) for both periods of the impact study. We have analyzed changes of the following climate impact indicators:

- i) The mean annual changes of precipitation, temperature, flow, snow water equivalent (SWE) and actual evapotranspiration.
- ii) The mean annual and mean seasonal changes of flow.
- 315 iii) The annual and seasonal flow duration curves (FDCs).
- iv) The timing of annual winter/spring and fall stream flow.
- v) The mean annual and seasonal maximum flows.
- vi) Floods with return periods of 2 to 200 years.

Changes are computed by Eq. (5) using the magnitudes of hydroclimatic variable for the reference and future periods.

$$Change\ in\ x(\%) = \left(\frac{Future\ value\ of\ x - Reference\ value\ of\ x}{Reference\ value\ of\ x} \right) * 100 \quad (5)$$

where x is any hydroclimatic variable.

2.4.1 Changes of hydroclimatic variables

315 The 3-hourly precipitation and temperature data, extracted from the climate model, are analyzed using an R-script to quantify the changes in the mean annual values for the reference and future periods. The 3-hourly precipitation data are aggregated yearly to estimate the annual precipitation value and then averaged over the 30 years to get the mean annual value. The 3-hourly temperature data are averaged for the whole 30 years to estimate the mean annual temperature. The simulated
320 3-hourly flow is averaged for the whole 30 years to get the mean annual flow data.

Seasonal mean flow data are also estimated for the reference and future periods i.e. winter, spring, summer and autumn for assessing changes in the seasonal mean flow. The annual maximum SWE is selected from each hydrological year and averaged for reference and future periods to get the mean annual maximum SWE for the two periods. The annual actual evapotranspiration is estimated by aggregating the actual evapotranspiration from the 3-hour simulation results and then averaged over 30 years to get the mean annual actual evapotranspiration.

2.4.2 Changes in flow duration curves

A flow duration curve is a cumulative curve that shows the percent of time a specified flow is equaled or exceeded during a given period, and it shows the flow characteristic of a stream throughout a range of flow, without regard to the sequence of occurrence (Searcy, 1959). We have analyzed changes in the stream flow variability over a water year between the reference and future periods. The changes of floods (between 0% and 10% exceedance), medium flows (between 10% and 70% exceedance) and low flows (between 70% and 100% exceedance) are analyzed in this study. The formula to calculate the probability of exceedance is given by Eq. (6).

$$p = 100 * K / (n + 1) \quad (6)$$

p = the probability that a given flow will be equaled or exceeded (% of time)

K = the ranked position on the listing (dimensionless)

n = the number of events for period of record, and it is dimensionless.

340

2.4.3 Changes in timing of annual winter/spring and fall stream flow

The annual timing of river flows is a good indicator of climate-related changes. Changes in timing of annual winter/spring (WS) and fall stream flow is analyzed using center of volume date
345 (Hodgkins et al., 2003). The center of volume date is the date by which half of the total volume of water for a given period flows by a river section. The center of volume date is expected to be more robust indicator of the timing of the bulk of high flows in a season than the peak flows, as the peak flow may happen before or after the bulk of seasonal flows (Hodgkins et al., 2003). From the 3-hour flow data (simulated for the reference and future periods), we have calculated the mean 3-
350 hour flow for the 30 years in both periods. Using the mean 3-hour flow, we have computed seasonal center of volume dates for the winter/spring (1 January to 31 May) and fall (1 October to 31 December).

2.4.4 Changes in the maximum flows and flood frequency

355 The annual and seasonal maximum flows (floods) are selected from the 30 years of reference and future periods for the analysis. The changes in the mean and median of the annual and seasonal maximum flows are analyzed.

The number of 3-hour floods (frequency) above a certain threshold helps us to have a general overview on the impacts of climate change on the flood risk in small catchments. Accordingly, we
360 have analyzed the changes in the number of 3-hour floods between the reference and future periods with a flow higher than the minimum of the 30 years annual maximum flow for the reference period.

To assess the magnitude of a flood with a given probability, flood frequency methods must be applied. Flood frequency analysis is important for flood hazard mapping, for which a flood of a certain return period (e.g. 200 years in Norway) is used for the flood zone mapping (Groen et al., 2012). To analyse changes in the magnitudes of a flood with a given return period (e.g. 200-year flood), flood frequency analysis is applied to the annual maximum series for the reference (1981 – 2011) and future periods (2070 – 2100). The percentage change in the flood magnitude is then computed as the difference between the two curves divided by the flood magnitude for the reference period. We have used a Gumbel distribution (Bhagat, 2017, Shaw, 1983) to model the annual maximum series in this study. We have selected the Gumbel distribution because it has been widely applied including the studies of climate change impacts on floods in Europe (Dankers and Feyen, 2008, Veijalainen et al., 2010).

375

3 Results

3.1 Regionalized DDD model parameters

The results of the parameters values from the regionalization for the six study catchments are presented in Table 3. The parameters and possible ranges of values are presented in appendix 4.

380 3.2 Changes in hydroclimatic variables

The simulation results of the hydrological model are further analyzed to quantify the changes in the hydroclimatic variables. The mean annual precipitation, the mean annual temperature, the mean annual evapotranspiration, the mean annual flow, the mean autumn flow, and the mean winter flow increase for all the study catchments in the future period compared to the reference period. The mean spring flow increases in the five catchments and decrease in one study

385

catchment. The mean summer flow decreases for the five catchments. The mean annual maximum SWE decreases for all the study catchments. In the future period, the mean annual precipitation increases by 20% to 24 %. The mean annual temperature rises in 3 - 3.3°C. The mean annual flow increases from 17% to 33%. The decrease in the mean summer flow ranges from 7% to 35% and the increase is 4% in only one of the study catchments. The mean winter flow increases by an average of 127% (ranging from 41% to 256%). The mean spring flow increases by 4% to 100% for the five catchments and there will be a decrease by 1% in one catchment. The mean autumn flow increases by an average of 37% (ranging from 21% to 43%). The results of changes of the mean annual temperature, precipitation, maximum SWE and actual evapotranspiration are presented in Table 4. Table 5 presents changes in the mean annual and seasonal flows for the catchments. Mean 3-hourly flow of the study catchments are shown in Fig. 3 for the reference and future periods.

3.3 Changes in flow duration curves

The results of the study show that changes in the flow duration curves (FDCs) values are positive for all the flow conditions. The FDC values of the future period increase for all flow conditions (low, medium and high flows) for all the study catchments. For all catchments, the top 5% of flows in the future period are higher than the reference period by 8% to 62%. The median flow (flows which are exceeded by 50% of the time) increases by 24% to 140% (the highest value is for catchment 1 and the lowest value is for catchment 4) in the future period. Figure 4 shows the FDCs for both periods.

3.4 Changes in timing of annual winter/spring (WS) and fall stream flow

For all the study catchments, the mean WS center of volume dates occur earlier in the future period
410 (16 - 68 days) than the reference period. The fall CV date occurs later for all the study catchments
in the future period and a shift of 1 – 16 days is expected. Table 6 presents the mean WS CV dates
and mean fall CV dates for all the study catchments.

3.5 Changes in the maximum flows and flood frequency

415 3.5.1 Changes in the annual and seasonal maximum flows

The annual and seasonal maximum flows increase in the future period compared to the reference
period. The mean annual maximum flows increase from 29% to 38% across all the study
catchments. The mean seasonal maximum flows also show an increase in all seasons (1 % to
118%) and all catchments except for spring season of catchment 2 (reduction of 29%) as shown in
420 Table 7. The median of the annual and seasonal maximum flows increases for all catchments
except for spring season of catchment 2 as shown in Fig.5. Table 7 presents the results of changes
in the mean annual and seasonal maximum flows in future period compared to the reference period.
Figure 5 shows the distributions of the 30 years annual and seasonal maximum flows both for the
reference and future periods.

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The number of 3-hours with floods exceeding the minimum annual maximum flood in the 30 years
of the reference period increases in the future period significantly (Table 8). This result shows that

flooding will occur more often in the future period. In the future period, the yearly average number of such floods increase by 62% to 133% across all study catchments.

430

3.5.2 Changes in flood frequencies

The flood frequency analysis using Gumbel's Extreme Value Distribution shows that floods of 2, 5, 10, 20, 25, 50, 100 and 200 years return periods increase in the future period (2070 – 2100) compared to the reference period (1981 – 2011) for all catchments. The increase ranges from 16% to 43%. Table 9 shows the changes of flood frequencies for the selected return periods for all the study catchments.

435

4 Discussion

4.1 Regionalized DDD model parameters

The physical similarity assessment, between the study and gauged catchments in the west climate region of Norway, shows that the most similar gauged catchments are located close to the study catchments. The assessment result shows that the regionalization method used in this study is plausible.

440

4.2 Hydrological impacts of climate change

4.2.1 Changes of hydroclimatic variables

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Generally, the findings of the increase in precipitation and temperature for the study catchments are in the range of increments predicted by the Norwegian Center for Climate Services (NCCS)

under the report Climate in Norway 2100 (Hanssen-Bauer et al., 2015) ; however, the results from some catchments are above or below the prediction interval of the report since the comparison is between catchments specific results with the regional values of the report. This is not unexpected since the comparison is between catchments specific values on a small scale and the regional values from the report. The NCCS report is based upon ten climate models with RCP8.5 and RCP4.5 using daily temporal resolution for the reference period (1971-2000) and future period (2071-2100).

The NCCS report shows that the median projections of change in the annual mean precipitation are 17% and 8% for RCP8.5 and RCP4.5 respectively, and projected increases in the mean annual temperature are by 3.7°C to 2.3°C for RCP8.5 and RCP4.5 respectively by 2100 for the south western part of Norway (where our study catchments are located). Our GCM-RCM-RCP8.5 result shows that the projected increase in the mean annual temperature is 3.3°C and the mean annual precipitation change is 22% between 1981-2011 and 2070-2100 periods at the Bergen area of Norway. The comparison shows that the GCM-RCM-RCP8.5 climate model, used in this study, predicts slightly more precipitation than the NCCS report for RCP8.5 and colder than the NCCS report with RCP8.5.

In the future period, all the study catchments show an increase in the mean annual flow compared to the reference period. The minimum and maximum increases are 17% and 33% respectively. Alcamo et al. (2007) found that the mean annual river flow is projected to increase in northern Europe approximately by 9% to 22% up to 2070. This result aligns with our findings i.e. the

470 increment could increase by 17% to 33 % by 2100. The increase in mean annual flow in the future period is a result of a substantial increase in projected mean annual precipitation with a moderate increase in mean temperature i.e. the mean annual precipitation increases by 20% to 24% while the mean annual temperature increases by 3°C to 3.3°C (Table 4). The increase in the mean annual temperature results in an increase of water loss by evapotranspiration. However, the mean annual
475 increase in precipitation exceeds the mean annual increase in the actual evapotranspiration computed in the model and these conditions contributed to increase of mean annual flow in general. The Hanssen-Bauer et al. (2015) report shows that the mean annual flow for western Norway (where the study catchments are located) could increase by -1% to 17% by 2100 and our result shows that the increase is slightly higher than the increase in the report for four of the study
480 catchments. This may very well be related to the higher resolution of our regional climate model. The higher resolution enables, at least in theory, a better local representation of precipitation and temperature, and the averaging issue in estimating the regional value by the report may lead to differences.

485 Unlike the changes in the mean annual flow, changes in the temporal distribution of flows (e.g. seasonal) can be important because changes are rarely identical throughout the year (Olsson et al., 2016). The mean winter and autumn flows increase for all study catchments. The main causes of increases are projected increase in the precipitation and temperature during the autumn and winter seasons. The increase in mean winter flow contributes to much of the increase in the mean annual
490 flow for all catchments (Table 5 and Fig.3). The main cause of increase in the mean winter flow is increased winter temperatures. Increased winter temperatures result in a higher proportion of winter precipitation to fall as rain which then results in a higher proportion of winter flow. The

mean spring flows show an increase for the five catchments and a decrease for one catchment while the mean summer flows show a decrease for the five catchments and an increase for one of the catchments. The increase in mean summer flow happened at a catchment which has the highest mean elevation (catchment 1 in table 1), and this result shows that the future increase in temperature may not result in high evapotranspiration to reduce the mean summer flows at the high elevation catchments.

Similar results are found in other hydrological assessments of the Bergen region. Previous studies of the water resources under climate change also project higher temperatures and increased annual precipitation in the Bergen region for the 2071-2100 future period under the RCP8.5 emissions scenario (Kristvik et al., 2018, Kristvik and Riisnes, 2015). Kristvik et al. (2018) based their assessment on statistical downscaling of an ensemble of RCPs and GCMs, followed by simulations of the hydrological response in term of inflow to surface water reservoirs. Due to higher temperatures and more rainfall precipitation, strong increases in winter flow was found, while a decrease was projected in spring/summer months due to less snowmelt (Kristvik et al. 2018).

The Hanssen-Bauer et al. (2015) report for western Norway shows that the mean winter and autumn flow increase by 15% to 42% and by 5% to 36% respectively by 2100. The findings of this study show that the increase in mean winter flow is higher than the maximum prediction reported by Hanssen-Bauer et al. (2015) for four catchments and to the higher end of the prediction in the report for the remaining two catchments. Similar results have been obtained for mean autumn flows except that three catchments have higher value than the maximum prediction value in the

515 report. The report predicts an increase of the mean spring flow by -9% to 17% and a decrease of
mean summer flow by 13% to 28% by 2100. The findings of this study show that the increase in
the mean spring flow is within the prediction interval of the report for three catchments and higher
than the maximum prediction values of the report for the remaining three catchments. Wong et al.
(2011) studied the differences in hydrological drought characteristics in summer season of Norway
520 between the periods 1961-1990 and 2071-2100 using the HBV hydrological model with daily
temporal resolution and found that substantial increases in hydrological drought duration and
drought affected areas are expected in Norway which aligns with our findings. The Ministry of the
Environment of Norway (2009) also pointed out that the summer flow in Norway is projected to
be reduced and supports the findings of our study.

525

Climate change affects the snowpack and the amount of water stored in the snowpack (SWE).
Increased winter temperature will generally lead to a reduction in snow storage and hence the mean
maximum SWE will also be reduced in the future. The results of this study show that there will be
a reduction in the mean maximum SWE at all the catchments in the future period. The reduction
530 ranges from 48% to 78%. The largest reduction is found to be at the catchment with the highest
mean elevation value (catchment 1). Snow accumulation and its characteristics are the results of
air temperature, precipitation, wind and the amount of moisture in the atmosphere. Therefore,
changes in these and other climatic properties can affect snowpack and hence maximum SWE. In
our study, there is an increase temperature for all study catchments in the future period, and the
535 increase resulted in the reduction of mean annual maximum SWE at all the study catchments.

4.2.2 Changes in flow duration curves (FDCs)

The results of this study show that climate change affects the FDCs of the study catchments. The future FDC is higher than the FDC of the reference period at all catchments for all probability of exceedances (Fig.4). The FDCs of all the study catchment show that the low flows increase in the future, and there will be longer periods with higher flows in the future period than in the reference period.

4.2.3 Changes in WSCV and fall CV dates

The mean winter/spring center of volume date (WSCV) will be earlier, and the mean fall CV date will be later for all the study catchments. The change in WSCV dates is related to the amount and timing of spring snowmelt and warmer winter temperature. The earlier mean WSCV date in the future period is the result of increased precipitation falling during a warmer winter, reduced snow storage, early snow melt and warmer spring temperature. The late occurrence of fall CV dates is related to the higher precipitation and temperature projected in fall in the future period. The warmer temperature in the future period makes the major proportion of future precipitation to happen as rain especially in the months of November and December which increases the future floods towards the end of a year and then the total flow volume in fall which makes the fall CV dates to occur later. The finding in our study is supported by the finding of Blöschl; G. et al (2017) i.e. in the southwestern part of Norway, there is a shift towards later floods due to climate change in the same period at the end of a year (October - December).

4.3 Changes in the maximum flows and flood frequency

560 4.3.1 Annual and seasonal maximum flows

In the future period (2070 – 2100), the results of this study show that there will be an increase in the mean and median of the annual and seasonal maximum flows (Table 7 and 8, and Fig.5) at all the study catchments except for the spring season of catchment 2. Most (15 – 23 of the 30 annual maximum floods) of the maximum annual flows happen during the autumn period (1st September to 30th of November) and therefore much of the contribution for the increment of the mean and median annual maximum flows comes from the autumn (Fig.5). The second largest contributor to the increment of the mean and median annual maximum flows is winter season (Fig.5). In the future period, the winter maximum flows increase in magnitude and frequencies as a substantial amount of precipitation falls as rain in a warmer climate. The mean summer maximum flows show the least increment in the future period (1% to 21%). The finding that mean annual maximum flows (floods) increase by 29% to 38% in our study is supported by Lawrence and Hisdal (2011). Lawrence and Hisdal (2011) have done ensemble modelling based on locally adjusted precipitation and temperature data from thirteen regional climate scenarios to assess likely changes in hydrological floods between a reference period (1960 – 1990) and two future periods (2021-2050) and (2071 - 2100), for the 115 catchments distributed throughout in Norway. Their results showed that western regions of Norway are associated with the largest percentage increases in the magnitude of the mean annual floods (> 20%). Lawrence and Hisdal (2011) also pointed out that increase in autumn and winter rainfall throughout Norway will increase the magnitude of peak flows during these seasons, and at areas already dominated by autumn and winter floods, the projected increases in floods magnitude will be large. Since our study catchments are at western Norway which is dominated by autumn floods and our finding (Fig.5) confirms their finding in

that the maximum increases in floods magnitude are expected to happen in autumn and winter seasons (Table 7 and Fig.5).

585 The yearly average number of 3-hours flows, which are greater than the minimum of the annual maximum high flows in the 30 years of the reference period increases. The yearly average number of such floods increase between 61.7% and 133% across all study catchments as presented in Table 8. The results show that there will be a greater number of 3-hours floods in the future period than the reference period, and more flood risks are expected at the infrastructures constructed
590 downstream of small ungauged rural catchments in west coast Norway near Bergen city. European Environmental Agency(2004b), in: Alcamo et al. (2007) found that the risk of floods increases in northern Europe (e.g. Norway) which supports our finding of increase in the risk of floods. Center for International Climate Research (<https://cicero.oslo.no>) predicts that western Norway will experience more heavy rain and flooding in the future and our findings confirms their predictions.

595

4.3.2 Changes in flood frequency

The study results from the six ungauged small catchments show that there will be an increase in flood frequencies with a return periods of 2, 5, 10, 20, 25, 50, 100, 200 years in the future period. The changes of all return periods for all catchments are in between 16% and 43%. The maximum
600 and the minimum changes happen for a return period of 200 years. For all return periods, the mean changes are between 31 % and 32% while the median changes are between 30% and 34%. The 2, 5, 10 years changes are greater than 20% for all catchments, and 20, 25, 50, 100 and 200-years changes are greater than 20% for five of the six study catchments.

605 Beldring et al. (2006) studied the percentage change in the mean annual flood and the 50-year flood in four catchments in Norway between 1961-1990 and 2070-2100 in which one of the catchments is in western Norway (Viksvatn in Gaular) and found that moderate to large increases are expected. Their result is supported by our finding i.e. the 50-year flood on six small catchments in west Norway will increase by 18% to 40 % between 1981 -2011 and 2070-2100. The results of
610 our study show that the 200-year flood changes range from 16% to 43% for the study catchments. Lawrence and Hisdal (2011) have found that the projected increase of the 200-year flood exceed 40% for some of the catchments in western Norway between the 1961-1990 reference period and the 2071- 2100 future period which is in agreement with our findings. Lawrence (2016) used ensembles of regional climate projections from EURO-CORDEX together with HBV model to
615 assess possible effects of climate change on floods on 115 catchments in Norway for two future periods (2031-2060 and 2071-2100). The assessment result shows that the minimum increase in the 200 years flood for catchments less than 100km² at Hordaland county (where the study catchments are located) is 20% which is generally in agreement with our findings.

620 Lawrence (2016) showed that the increase in the 200 years flood is higher for RCP8.5 than RCP 4.5 in Hordaland county. Not surprising that the choice of RCP has significant effect on the results of the 200years flood frequency. Of the 115 catchments used in the study for the whole Norway, 10 of them are in the Hordaland county. With emission scenario RCP4.5, eight of the ten catchments showed less than 20 % increase (1 catchment a decrease, 2 catchments an increase
625 between 1% - 10%, 5 catchments an increase between 11% - 20%), and two catchments show an increase greater than 20% (1 catchment an increase between 21% - 30% and 1 catchment an

increase between 31% - 40%. With emission scenario RCP8.5, seven of the ten catchments show greater than 20 % increase (3 catchments an increase between 21% - 30% and 4 catchments an increase between 31% - 40%), and 3 catchments show an increase of less than 20% (1 catchment a decrease and 2 catchments an increase between 11% - 20%). The result of our study shows that the 200-year flood changes range from 16% to 43% (1 catchment between 10% -20%, 1 catchment between 20% -30%, 2 catchments between 30% - 40% and 2 catchments between 40% and 50%). Generally, our finding with RCP8.5 is similar to the Lawrence (2016) finding with RCP8.5 except that our finding shows an increase greater than 40% for some study catchments.

The main differences between our study and the study of Lawrence (2016) are the number and types of climate models, RCPs, the catchment sizes and the temporal resolution. The comparisons of the increase in flood risks are mainly done in the same county (Hordaland county where Bergen area is located) and the area is mainly dominated by floods generated by rain in autumn season. However, in the Lawrence (2016) study the catchment sizes are ranging from 6km² to 15449km² and used 10 global-regional models with RCP8.5 and RCP4.5. The temporal resolution used in the Lawrence (2016) study is daily and perhaps this is the data which has been bias corrected after the GCM-RCM chain. Changes above 41% for some catchments in our findings are related with the differences in the climate models, differences in the bias correction method, difference in the temporal resolutions used, difference in the hydrological models used, differences in the sizes of the catchments and capability of the DDD model in predicting 3 hourly floods in small catchments. Our findings are based on RCP8.5 scenario which can be used as a worst-case scenario at the Bergen area in the south western part of Norway.

650 4.4 Limitations

There are limitations in this study which are related to DDD model and the climate model. A first limitation is related to the DDD model parameters. In this study, we have used the regionalization of DDD model parameters developed for 1 hour (Tsegaw et al., 2019a) to estimate parameters for the 3-hour simulation. DDD model parameters like degree hour factor for evapotranspiration (C_{ea}) and degree hour factors for snow melt (C_x) can be sensitive to the temporal resolution. However, the same uncertainty is present both in the reference and future period. The second limitation is related to the simple degree evaporation model used in the DDD. Table 4 shows big changes in actual evapotranspiration, and the big change in actual evapotranspiration tells us that in the future period there will be higher water available (to evaporate) and higher temperature (to cause evaporation) than the reference period; however, there is a limitation with the simple evaporation model since actual evaporation is not only affected by temperature but by additional climatological factors like wind speed, humidity, cloudiness etc. This limitation could also be the reason for a big change of actual evapotranspiration between the reference (1981-2011) and future period (1970-2100). A third possible limitation is that the DDD model parameters are assumed to be constant under changing climatic conditions, and the same parameter sets are used for the reference and future period simulations. However, studies show that using the same parameter sets for the reference and future periods under climate impact studies can have significant impact on the simulation results (Merz et al. (2011)). A fourth limitation is that the modelled changes in the hydroclimatic variables and flood frequency are derived from a single GCM-RCM model chain using only the RCP8.5 scenario. Thereby, we are not able to capture the GCM-RCM uncertainties usually found by handling model ensembles. However, this simulation has the benefit of a high spatial resolution for a better representation of small-scale features and additionally a novel bias

correction method has been applied prior to the downscaling to ensure physical consistency between temperature and precipitation variables used as input to the hydrological model.

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We present one realization of a climate scenario, and that we recommend applying the method of Pontoppidan (2018) to other GCMs to capture model uncertainties. Further, the comparison done between our study and other studies shows that we are not totally off, and that the findings can give a useful addition to the current understandings of the effects of changing climate on the west coast. Other combinations of GCMs-RCMs-RCPs predict varieties of future climate change signals which could potentially result in different hydroclimatic and flood predictions for the same study catchments. Therefore, the results of this study alone should not be taken as a conclusive of what will be seen in the future but could be of practical use to regional decision-makers if considered alongside other previous and future findings.

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5 Conclusion

In this study we use a newly developed bias corrected dynamical downscaling product as input for the DDD model to investigate the impact of climate change on small ungauged catchments in western Norway. The results show that there will be an increase in the mean annual flow in the future period. The increase in the mean annual flow is due to the increase in the mean autumn, winter and spring flows in the future period (2070-2100) compared to the reference period (1981 - 2011). In the future period, the mean summer flows from the study catchments decrease. Future flow duration curves are higher than the flow duration curves of the reference period for all study catchments for all probability of exceedances. The median flow (flows which are exceeded by

695 50% of the time) increases by 24% to 140%. The FDCs of all the study catchment show that the low flows increase in the future, and there will be more wetter periods in the future than in the reference period.

There will be an increase in the mean annual floods and flood frequencies of 2, 5, 10, 20, 25, 50, 700 100 and 200 years in the future period. The mean annual maximum floods increase by 28.9% to 38.3%. This study gives clear indication that the projected increase in flood frequencies are high (e.g. 200-year flood > 40%) in small catchments around Berge area of western Norway, and such catchments are vulnerable to an increased risk in the future climate. The high-resolution regional climate model with a novel bias correction method improves the knowledge and understanding of 705 climate change impacts on hydrology of small catchments in western Norway. However, it is important to conduct further research which can address the limitations of this study before conducting flood risk assessment and planning flood risk management strategies as a national strategy for climate change adaptation.

710 These simulations are based on high resolution regional climate model projection with a novel bias correction method and address limitations in previous impact studies where such projections have not yet been available and enabling in-depth analysis of the impacts of climate change on rapid hydrological processes. An ensemble of GCM-RCM runs building on the results of this paper is suggested as a venue for further work in order to account for uncertainties in future emissions and 715 climate projections and thus provide more reliable recommendations for infrastructure design and adaptation.

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Appendixes

Appendix 1. List of DDD model parameters estimated from observed precipitation data and those estimated from regionalization (multiple regression) for the study catchments.

Parameters	Description of the parameter	Method of estimation	Unit
d	Parameter for spatial distribution of SWE, decorrelation length	From spatial distribution of observed precipitation	Positive real number
a0	Parameter for spatial distribution of SWE, shape parameter	From spatial distribution of observed precipitation	Positive real number
MAD	Long term mean annual discharge	Specific runoff map of Norway	$\text{m}^3 \text{sec}^{-1}$
Gshape	Shape parameter of λ	Regression	Positive real number
Gscale	Scale parameter of λ	Regression	Positive real number
GshInt	Shape parameter of Λ	Regression	Positive real number
GscInt	Scale parameter of Λ	Regression	Positive real number
Fc	Critical flux	Regression	m^3/hour

1035 **Appendix 2.** List of DDD rainfall-runoff model parameters estimated from pooling group of
 physical similarity method of regionalizations.

	Parameters	Description of the parameter	Method of estimation	Unit
1040	Pro	Liquid water in snow	Regionalization (poolig group)	fraction
	Cx	Degree hour factor for snow melt	Regionalization (poolig group)	mm °C ⁻¹ hour ⁻¹
	CFR	Degree hour factor for refreezing	Regionalization (poolig group)	mm °C ⁻¹ hour ⁻¹
	Cea	Degree hour factor for evapotranspiration	Regionalization (poolig group)	mm °C ⁻¹ hour ⁻¹
	rv	Celerity for river flow	Regionalization (poolig group)	m/s

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Appendix 3. List of DDD rainfall-runoff model parameters estimated from geographical data using GIS.

Symbol of parameters	Description of the Parameter
area	Catchment area
maxLbog	Maximum distance of marsh land portion of hillslope
midLbog	Mean distance of marsh land portion of hillslope
bogfrac	Areal fraction of marsh land from the total land uses
zsoil	Areal fraction of DD for soils (what area with distance zero to the river)
zbog	Areal fraction of distance distribution for marsh land (what area with distance zero to the river)
midFl	Mean distance (from distance distribution) for river network
stdFL	Standard deviation of distance (from distance distribution) for river network
maxFL	Maximum distance (from distance distribution) for river network
maxDl	Maximum distance (from distance distribution) of non-marsh land (soils) of hill slope
midDL	Mean distance (from distance distribution) of non-marsh land (soils) of hill slope
midGl	Mean distance (from distance distribution) for Glacial
stdGl	Standard deviation of distance (from distance distribution) for Glacial
maxGl	Maximum distance (from distance distribution) for Glacial
Hypsographic curve	11 values describing the quantiles 0, 10, 20, 30, 40, 50, 60,70,80,90,100

Appendix 4. Possible ranges of regionalized DDD model parameters

Model parameters needing regionalization	Method of regionalization	Possible ranges of values
Gshape	Multiple regression	Positive real number
Gscale	Multiple regression	Positive real number
GshInt	Multiple regression	Positive real number
GscInt	Multiple regression	Positive real number
fc	Multiple regression	Positive real number
Pro	Pooling group type of physical similarity	0.03 - 0.1
Cx	Pooling group type of physical similarity	0.05 - 1.0
CFR	Pooling group type of physical similarity	0.001 - 0.01
Cea	Pooling group type of physical similarity	0.01 - 0.1
rv	Pooling group type of physical similarity	0.5 - 1.5

Figure Captions

Figure 1. Locations of study catchments in Norway

Figure 2. Structure of the Distance Distributions Dynamics model adapted from Skaugen and Onof (2014). Left panel: the storage model and right panel: hydrographs of hillslope and river. P is precipitation, T is temperature, E is actual evapotranspiration, G(t) is input from snowmelt and rain, Z(t) is soil moisture in unsaturated zone, X(t) is excess water, M is total volume of subsurface water reservoir, S(t) a saturated zone volume and D (t) is unsaturated zone volume.

Figure 3. Yearly mean 3 hourly hydrographs of the study catchments for the reference and future periods.

Figure 4: Flow duration curves (FDCs) of the 3-hourly flow for the six study catchments both for the reference and future periods using bias corrected NorESM1-M (r1i1p1) global climate model, WRF regional climate model and RCP 8.5.

Figure 5. Distributions of the annual and seasonal maximum flow values of the 30 years period.

Figures

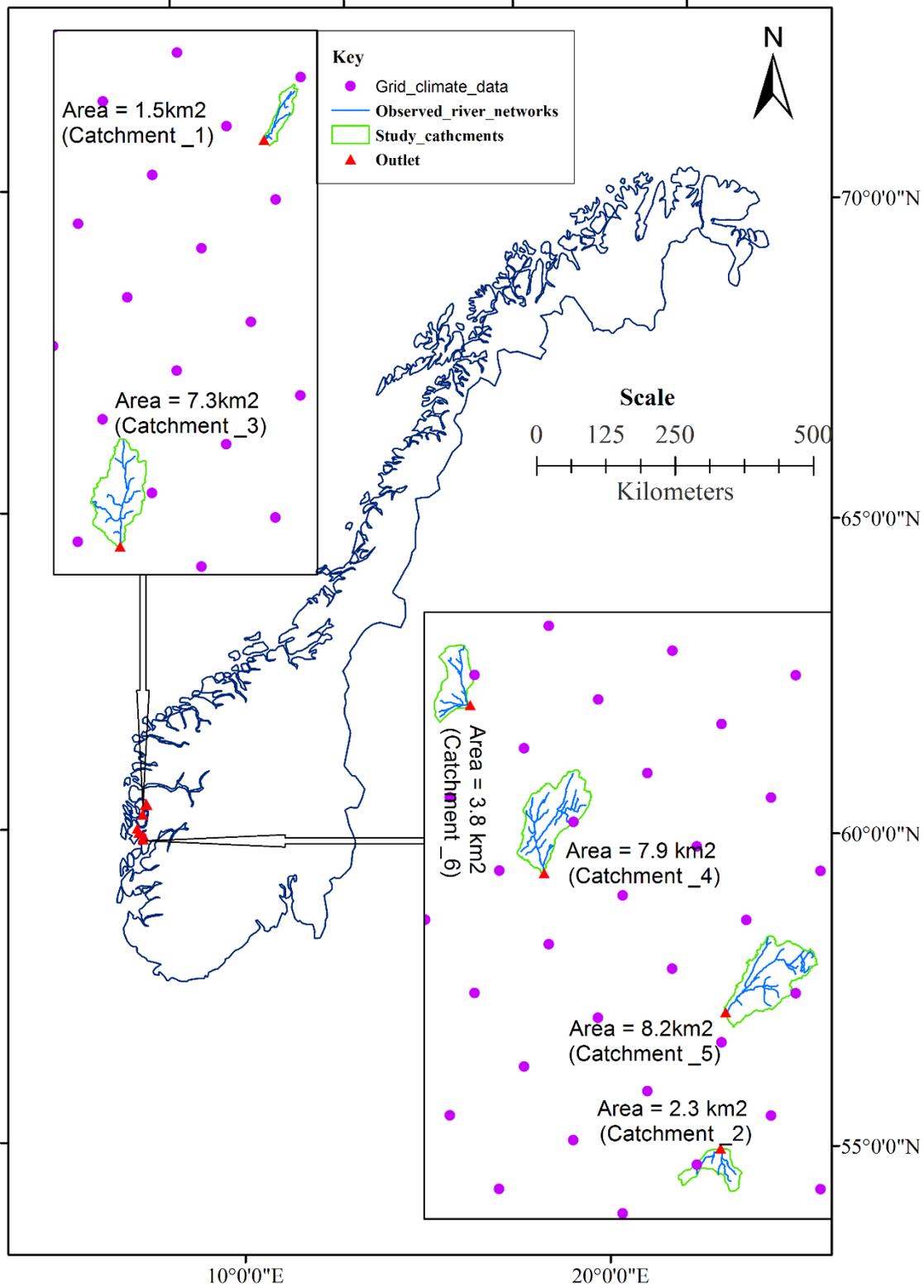


Figure 1. Locations of study catchments in Norway.

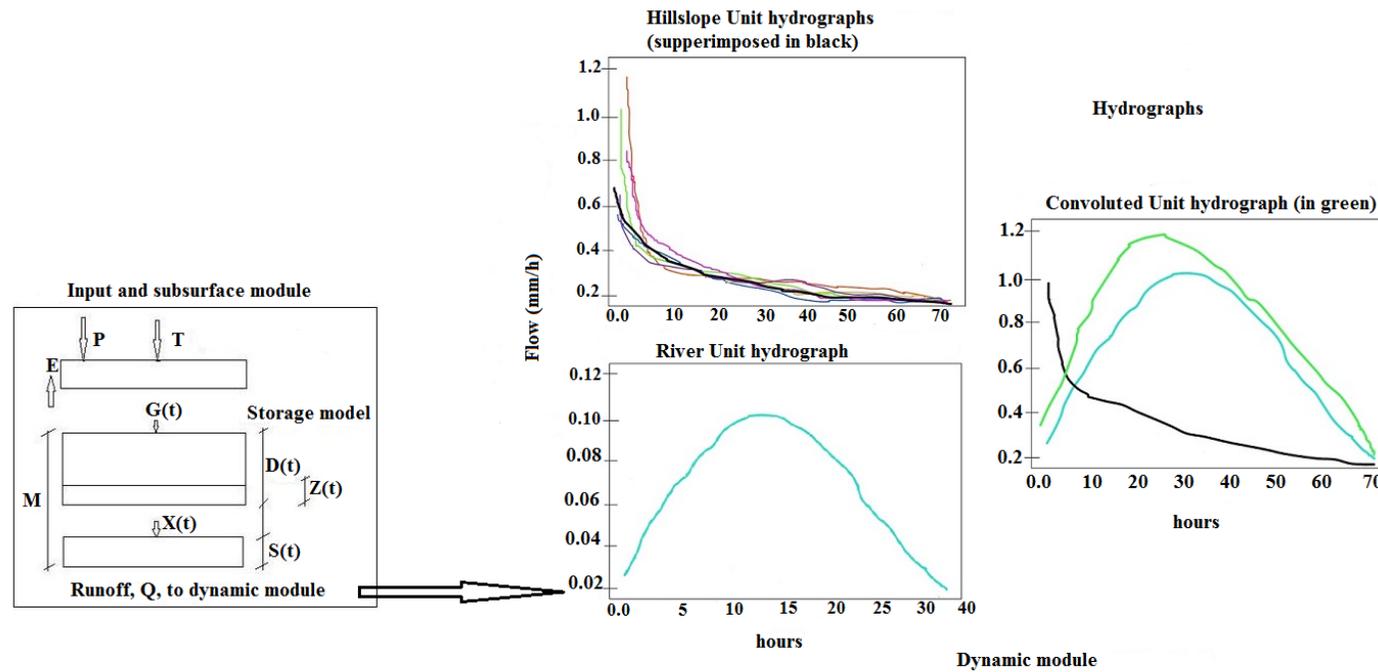


Figure 2. Structure of the Distance Distributions Dynamics model adapted from Skaugen and Onof (2014). Left panel: the storage model and right panel: hydrographs of hillslope and river. P is precipitation, T is temperature, E is actual evapotranspiration, G(t) is input from snowmelt and rain, Z(t) is soil moisture in unsaturated zone, X(t) is excess water, M is total volume of subsurface water reservoir, S(t) a saturated zone volume and D (t) is unsaturated zone volume.

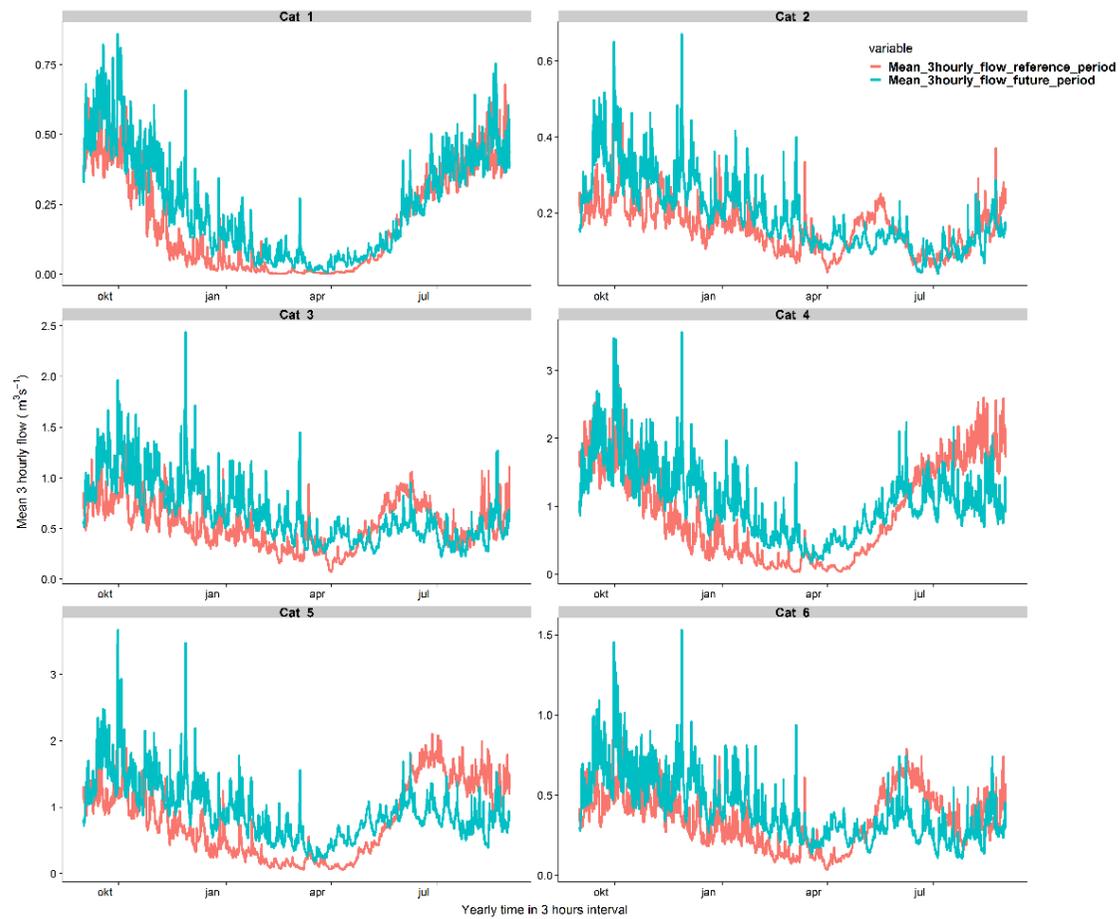


Figure 3. Yearly mean 3 hourly hydrographs of the study catchments for the reference and future period.

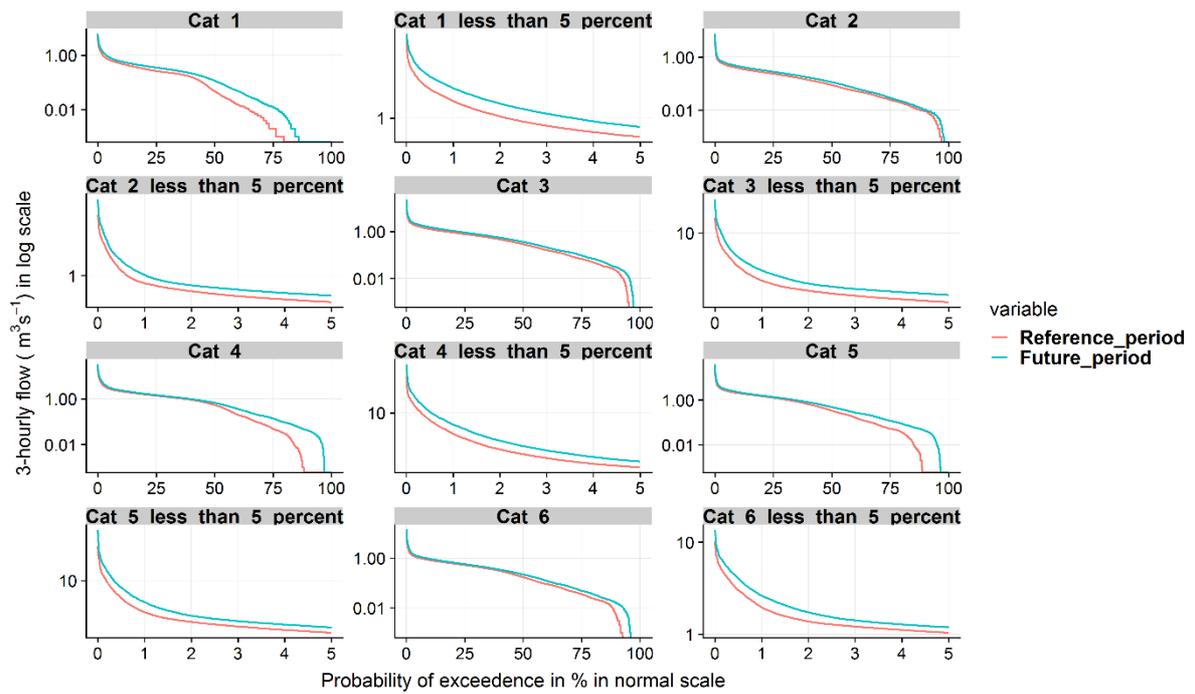


Figure 4: Flow duration curves (FDCs) of the 3-hourly flow for the six study catchments both for the reference and future period.

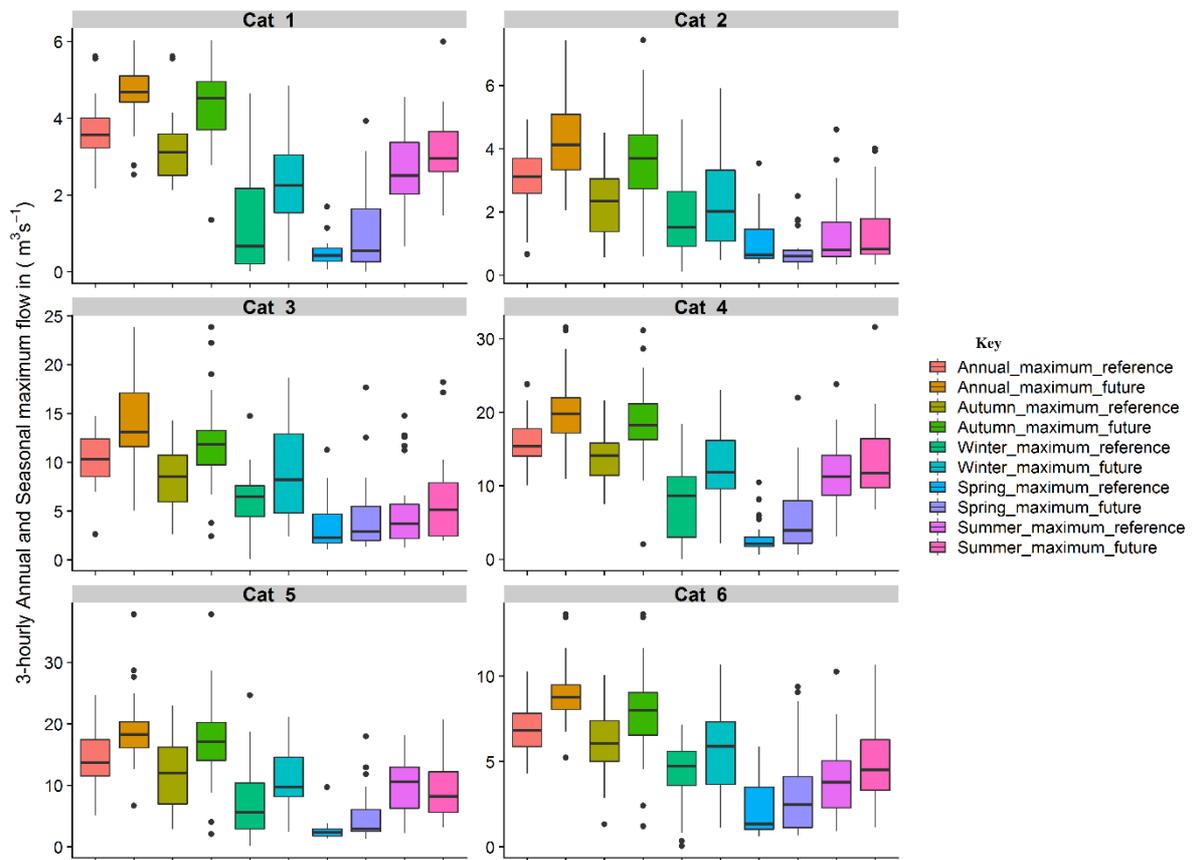


Figure 5. Distributions of the annual and seasonal maximum flow values of the 30 years period.

Tables

Table 1: Catchment descriptors of the study catchments

Catchments Descriptors	Unit	Symbol	Catchments					
			Cat_1	Cat_2	Cat_3	Cat_4	Cat_5	Cat_6
Mean of distance distributions of soils in the catchment to the nearest river reach	<i>m</i>	D _m	103.0	169.1	204.3	137.0	174.9	171.7
Mean of distance distributions of marsh land in the catchment to the nearest river reach	<i>m</i>	D _{mr}	0.0	261.0	220.7	109.9	107.2	154.3
Mean of distance distribution of points in the river to the outlet	<i>m</i>	D _r	1513.2	960.5	2671.2	3061.1	3402.8	1733.3
Catchment area	<i>km</i> ²	A	1.5	2.3	7.3	7.9	8.2	3.8
Effective lake	%	L _e	0.2	0.0	0.0	0.7	0.0	0.0
Forest	%	F	18.5	65.3	75.8	22.5	69.7	25.4
Bare mountain	%	B	79.6	27.6	14.8	66.0	18.9	65.3
Urban	%	U	0.0	0.1	0.0	0.0	0.0	0.0
Mean elevation	<i>m</i>	M _e	684.6	322.1	314.7	461.5	402.1	466.7
Mean anual precipitation	<i>mm</i>	M _p	3268.0	2243.0	2500.0	2781.0	2543.0	2644.0
Speciifc discharge	<i>l s</i> ⁻¹ <i>km</i> ⁻²	S _q	141.0	115.7	91.8	125.6	134.2	110.7
Mean river slope	<i>m km</i> ⁻¹	R _s	162.6	266.2	88.4	106.4	118.6	154.9
Outlet location								
ETRS_1989_UTM_Zone_33N coordinate system (m)	Longtiude		-9376.0	-14513.6	-15886.7	-22440.2	-14280.8	-25871.8
	Latitude		6777231.6	6712810.0	6758694.5	6725236.5	6719015.4	6732970.8

Table 2: Coefficients of the power relation between D_m and A_c and the coefficients of determination (R-squared).

Catchment_ID	a	b	R-squared
Cat_1	1.42	0.41	0.97
Cat_2	0.87	0.45	0.99
Cat_3	0.87	0.46	1
Cat_4	1.2	0.44	0.99
Cat_5	0.99	0.45	1
Cat_6	0.87	0.46	1

Table 3: DDD model parameters of the study catchments estimated from regionalization

Model parameters needing regionalization	Catchments					
	Cat_1	Cat_2	Cat_3	cat_4	Cat_5	cat_6
Gshape	2.317	1.827	1.977	2.087	1.961	2.032
Gscale	0.041	0.036	0.034	0.033	0.038	0.037
GshInt	4.085	3.083	3.39	3.615	3.356	3.502
GscInt	0.018	0.016	0.015	0.015	0.017	0.017
fc	49.3	122.1	140.00	68.30	134.2	69.00
Pro	0.1	0.087	0.082	0.100	0.095	0.096
Cx	0.155	0.129	0.108	0.137	0.159	0.147
CFR	0.004	0.006	0.007	0.004	0.003	0.004
Cea	0.033	0.025	0.016	0.032	0.028	0.031
rv	1.22	1.240	1.17	1.200	1.260	1.190

Table 4: Changes of mean annual temperature and precipitation, mean annual maximum snow water equivalent (SWE) and mean annual evapotranspiration for all the study catchments using bias corrected NorESM1-M (r1i1p1) global climate model, WRF regional climate model and RCP 8.5.

Hydro-meteorological indicator	Unit	Change in indicator
Cat_1		
Mean annual precipitation	mm	22 %
Mean annual temprature	°C	3.3 °C
Mean annual maximum SWE	mm	-78 %
Mean annual evapotranspiration	mm	63 %
Cat_2		
Mean annual precipitation	mm	24 %
Mean annual temprature	°C	3.1 °C
Mean annual maximum SWE	mm	-48 %
Mean annual evapotranspiration	mm	67 %
Cat_3		
Mean annual precipitation	mm	24 %
Mean annual temprature	°C	3.2 °C
Mean annual maximum SWE	mm	-50 %
Mean annual evapotranspiration	mm	43 %
Cat_4		
Mean annual precipitation	mm	20%
Mean annual temprature	°C	3.2 °C
Mean annual maximum SWE	mm	-56 %
Mean annual evapotranspiration	mm	132 %
Cat_5		
Mean annual precipitation	mm	22 %
Mean annual temprature	°C	3.2 °C
Mean annual maximum SWE	mm	-49 %
Mean annual evapotranspiration	mm	81 %
Cat_6		
Mean annual precipitation	mm	20.0 %
Mean annual temprature	°C	3.0 °C
Mean annual maximum SWE	mm	-63.0 %
Mean annual evapotranspiration	mm	92 %

Table 5: Changes in percentage of mean annual flow and seasonal flows of the study catchments. The unit of the flows is m³/s.

Hydrologic indicator (flow)	Change in indicator (%)	Hydrologic indicator (flow)	Change in indicator (%)
Cat_1		Cat_4	
Mean annual flow	33	Mean annual flow	17
Mean winter flow	256	Mean winter flow	168
Mean spring flow	49	Mean spring flow	100
Mean summer flow	4	Mean summer flow	-33
Mean Autumn flow	44	Mean Autumn flow	21
Cat_2		Cat_5	
Mean annual flow	22	Mean annual flow	19
Mean winter flow	41	Mean winter flow	147
Mean spring flow	-1	Mean spring flow	76
Mean summer flow	-7	Mean summer flow	-41
Mean Autumn flow	38	Mean Autumn flow	43
Cat_3		Cat_6	
Mean annual flow	22	Mean annual flow	17
Mean winter flow	68	Mean winter flow	81
Mean spring flow	4	Mean spring flow	10
Mean summer flow	-21	Mean summer flow	-35
Mean Autumn flow	41	Mean Autumn flow	35

Table 6: Winter/spring and fall centre of volume (CV) dates for the six study attachments

Annual timing	CV date (reference)	CV date (future)	Is CV date early or late?
<i>Cat_1</i>			
Winter/Spring	13 May	5 March	early
Fall	21 October	31 October	late
<i>Cat_2</i>			
Winter/Spring	18 March	2 March	early
Fall	11 November	12 November	late
<i>Cat_3</i>			
Winter/Spring	27 March	3 March	early
Fall	8 November	11 November	late
<i>Cat_4</i>			
Winter/Spring	24 April	10 march	early
Fall	29 October	8 November	late
<i>Cat_5</i>			
Winter/Spring	26 April	13 March	early
Fall	3 November	19 November	late
<i>Cat_6</i>			
Winter/Spring	11 April	3 March	early
Fall	8 November	11 November	late

Table 7: Changes in percentage of the mean annual and seasonal maximum flows in the future period compared to the reference period.

Annual and Seasonal maximum flows	Change in indicator (%)	Annual and Seasonal maximum flows	Change in indicator (%)
<i>Cat_1</i>		<i>Cat_4</i>	
Mean autumn maximum flow	38	Mean autumn maximum flow	33
Mean winter maximum flow	82	Mean winter maximum flow	60
Mean spring maximum flow	118	Mean spring maximum flow	106
Mean summer maximum flow	17	Mean summer maximum flow	18
Mean annual maximum flow	28	Mean annual maximum flow	29
<i>Cat_2</i>		<i>Cat_5</i>	
Mean autumn maximum flow	60	Mean autumn maximum flow	48
Mean winter maximum flow	32	Mean winter maximum flow	49
Mean spring maximum flow	-29	Mean spring maximum flow	86
Mean summer maximum flow	7	Mean summer maximum flow	1
Mean annual maximum flow	38	Mean annual maximum flow	31
<i>Cat_3</i>		<i>Cat_6</i>	
Mean autumn maximum flow	43	Mean autumn maximum flow	28
Mean winter maximum flow	46	Mean winter maximum flow	29
Mean spring maximum flow	25	Mean spring maximum flow	41
Mean summer maximum flow	21	Mean summer maximum flow	27
Mean annual maximum flow	37	Mean annual maximum flow	29

Table 8: Changes in the number of 3-hour floods which are greater than the minimum annual maximum flood in the reference period for all the study catchments.

Catchment ID	Mean annual number of 3-hours floods greater than the minimum annual maximum flood in the reference period		Changes in number (%)
	Reference period (1981-2011)	Future period (2070-2100)	
<i>Cat_1</i>	9.1	21.2	133.0
<i>Cat_2</i>	58	99.3	71.2
<i>Cat_3</i>	38	64.4	69.5
<i>Cat_4</i>	9	15.4	71.1
<i>Cat_5</i>	22.2	35.9	61.7
<i>Cat_6</i>	7	13.3	90

Table 9: Changes of flood frequencies with return periods of 2, 5, 10, 20, 25, 50, 100 and 200 years between the future and reference periods using Gumbel's Extreme Value Distribution for all study catchments.

T(years)	Change (%)					
	Cat_1	Cat_2	Cat_3	Cat_4	Cat_5	Cat_6
2	29	37	36	28	31	30
5	24	36	38	33	31	27
10	22	36	39	36	31	26
20	20	35	40	38	31	25
25	20	35	40	39	31	25
50	18	35	41	40	31	24
100	17	35	41	42	31	23
200	16	35	41	43	31	23