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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 minor revision.

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

The main comments/concerns of the second reviewer are: the difficulties to understand the bias correction method in the methodology section of the manuscript, comments made in the first PDF were not addressed satisfactorily, and language and presentation of results are not precise.

To address the comment related to bias correction method, we have revised the whole paragraph and the mathematical equations in the revised manuscript. We have explained how the monthly mean time series was computed and how the deviations were calculated in the revised paragraph.

To address the comments related to comments made in the first PDF, we have re-considered and addressed comments made in the first PDF (listed here and not listed here by the reviewer) in the revised manuscript.

To address the comment related to language and presentation of results, we went through the whole manuscript carefully and revised sentences which had wrong grammatical expressions.

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

Best Regards,

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Knut Alfredsen

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Erle Kristvik

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

We would like to thank reviewer # 2 for the second-round 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 reviewer raised.

## **Reviewer # 2**

### **General comment**

The manuscript has improved with the first revision, especially with regard to a better embedding of the results with other research on climate change impacts in Norway and also the shortening of the DDD-model description is appreciated. However, further improvements are required. What I find somewhat discouraging here from the point of view of the reviewer is that many comments I made in the first PDF were simply ignored. I will only list a few examples here and expect that if the authors get the chance to resubmit the manuscript, the comments of the first round will also be taken into account.

### ***General Answer***

*Thank you. We have re-considered and addressed comments made in the first PDF. We have also revised the manuscript based on the new comments, which helped us for improving the manuscript.*

## Detailed comments

### 1) Examples of comments from the first round of reviews not addressed by authors

On page 3, line 57. It was already commented in the previous review that this sentence is not really elegant: "Climate change adverse results upon streamflow regimes worldwide..." Better start like this: "Adverse effects of climate change on river regimes worldwide..."

There is still the sentence in the introduction (page 3, line 61): "Projected increase in the frequency and intensity of heavy localized precipitation events, based on climate models, contributes to increasing in precipitation-generated local flooding, ..." To me, this sounds like the "projected increase of heavy localized precipitation events" itself cause an increase of local flooding in reality. Maybe it is simply the term "contributes", which is not used properly in this context.

Page 4, line 84: "Climate impact assessment on hydrology ... is challenging..." More correct or precise: "Assessing the impacts of climate change on hydrology...is challenging..." Moreover, the sentence is way too long.

### *Answer*

*We have revised the sentence on page 3, line 57 to make the sentence elegant as suggested by the reviewer. The revised sentence is found on page 3, lines 58-59 in the revised manuscript.*

*We have revised the sentence on page 3, line 61 to make the sentence precise as suggested by the reviewer. The word contribute has been removed. The revised sentence is found on page 3, lines 62- 64 in the revised manuscript.*

*We have revised the sentence on page 4, line 84 to make the sentence more correct. We kept the long sentence as it is because it contains important information on the challenges of climate impact study on hydrology of small ungauged catchments. The revised sentence is found on page 4, lines 83-87 in the revised manuscript.*

*We have also re-considered and addressed other comments made in the first PDF (not listed here by the reviewer) in the revised manuscript. The revisions are highlighted with yellow in the revised manuscript.*

## **2) Description of bias correction method**

page 9 (bottom) and page 10 (top): From the description, it is not clear to me how the bias correction was performed. I could only guess.

The sentence: "For the reference period the 6-hourly NorESM1-M input data were split into a monthly mean term and the deviation from this." is not clear.

First of all, the reader does not know whether the mean monthly time series is composed of twelve values, representing the 30-years mean or if it is a time series composed of  $12 \times 30$  values. I would also not use the term "split into". Explain first how the monthly mean time series was computed and then how the deviations were calculated. The equations 1-3 are not referred to in the text and are not self-explanatory, because the variables are not explained. Which variable represents the mean, which the deviation?

### ***Answer***

*Thank you. To address the concern related to the difficulties in understanding of the bias correction method specifically the mathematical description part on pages 8 and 9, we have revised the whole paragraph and the mathematical equations in the revised manuscript. We have explained how the monthly mean time series was computed and how the deviations were calculated in the revised paragraph. We have revised and increased the equations from 3 to 4 and described them in the body of the manuscript. The revision is found on page 12(bottom) and 13(top), lines 212-235 in the methodology section of the revised manuscript.*

### **3) Proper and / or imprecise use of English language**

It seems to me that the manuscript was not corrected by a native speaker. There are still sentences, which are grammatically not entirely correct. Sometimes it is only a missing "the" ...

#### ***Answer***

*To address the concern related to language, we went through the whole manuscript carefully and revised sentences which had wrong grammatical expressions.*

### **4) Discussion**

It seems that there is quite some redundancy between Discussion and Results and sometimes one and the same results are referred to too often. For example: "the magnitude of the 200-year flood changes range from 16% to 43%" (page 28, line 610 and page 29, line 631). So, there is some space for improvement.

#### ***Answer***

*Thank you. We have removed the sentence, which is found on page 28, line 610. The sentence on page 29, line 631 has been moved to the top and revised. The revision is found on page 38, lines 655-660 in the revised manuscript and highlighted with yellow. The repetitions of results in the discussions have been removed in the revised manuscript.*

### **Specific comments**

1) Page 2, line 26: RCPs are not "emission" scenarios but "greenhouse gas concentration" scenarios. It is also used somewhere else in the text.

#### ***Answer***

*Thank you. We have removed the word “emission” from whole manuscript in the revised version. Therefore, it will be read as RCP8.5 or 4.5 scenario.*

2) page 5, line 110: How can the performance of a simulation been measured if there are no observations? "Even if the DDD model predicts flow at ungauged catchments satisfactory  $0.5 \leq \text{Kling-Gupta Efficiency} < 0.75$ )..."

***Answer***

*We have already evaluated the performance of DDD model in predicting flows at small ungauged catchments in Norway using observed flow data with a recently published paper (Tsegaw et al.,2015). From the model test results, we know that the model predicts flow at ungauged small catchments satisfactorily in Norway. We have included the reference in the revised manuscript. The reference is found on page 5, line 113 in the revised manuscript.*

3) Page 6, line 137 "...dominated by rain floods..." I think, "rain flood" is not a proper term, it is either a river flood, if you want to distinguish from e.g. "coastal flood" or a flood caused by (heavy) rainfall.

***Answer***

*The sentence with the word “...dominated by rainfall” has been revised and replaced by “...a rainfall-dominated floods ....”. The revision is found on page 6, line 138 in the revised manuscript.*

4) page 9, line 207: Reference Bruyere et al. 2015 is not in the references. Is it Bruyere et al. 2014?

***Answer***

*Thank you. We have put the correct reference and removed Bruyere et al. 2014. The correct reference is Bruyère, C. L., Monaghan, A. J., Steinhoff, D. F., and Yates, D. Bias-Corrected CMIP5 CESM Data in WRF / MPAS Intermediate File Format. NCAR Technical Note NCAR/TN-515+STR, 2015. The included reference is found in the reference section of the revised manuscript.*

5) page 11, line 246: Be more specific: "catchments from small to large", what does it mean in terms of km<sup>2</sup>? "Temporal resolution from low to high", what is low what is high?

***Answer***

*We have described in detail by giving examples to small, large, high and low terms in the revised manuscript. The revision is found on page 14, lines 257-258 in the revised manuscript.*

6) page 14: The brackets in equation 5 are in my opinion superfluous.

***Answer***

*We agree that with and without the brackets have the same meaning, however; we kept the bracket as it is to make the equation clearer.*

7) page 14, line 315-320: You could simply say that the 3-hourly time series were converted to annual time series instead of writing 5 lines.

***Answer***

*Thank you. We have shortened the bottom four lines of the paragraph into two lines. The revision is found on page 19, lines 344-345 in the revised manuscript.*

8) page 17, lines 388f. ...temperature rises "in" <-- "by". The mean annual flow increases "from" <-- "between".

***Answer***

*Thank you. We have revised the sentences as per the reviewer suggestion. The revisions are found on page 22, lines 416 - 417 in the revised manuscript.*

9) page 19, line 410: Abbreviation "CV" not introduced before usage

***Answer***

*Thank you. We wrote centre of volume in the methodology section but forgot to include CV under bracket. We have introduced CV under bracket in the revised manuscript i.e. centre of volume (CV). The revision is found on page 20, line 370 in the methodology section of the revised manuscript.*

10) page 22, line 471: "moderate increase in temperature". 3 degrees increase is not moderate in



my point of view, only if you compare it to other world regions, where increase in air temperature might be much higher at the end of the 21st century.

***Answer***

*Thank you. We have removed “moderate” and “substantial” words from the sentence, and the sentence has been revised. The revision is found on page 32 and 33, lines 525 -526 in the revised manuscript.*

**11)** page 24, line 515: ...increase of...-9% to 17%... is it really -9%, if yes, increase would be the wrong term

***Answer***

*The sentence has been revised. It is actually -9%, and we have rephrased it as “....will reduce up to 9%”. The revision is found on page33, lines 563-565 in the revised manuscript.*

**12)** page 28, line 610: You present the value of the 50-year flood by another study and compare it to the 200-year flood from your study. Why don't you refer to the 50-year flood value from your study?

***Answer***

*Thank you. We have made minor revisions to the sentences and paragraphs under 4.3.2 i.e.*

***Changes in flood frequency.** We put the summary of our findings in the first paragraph, and we focused on the findings of other studies and the comparison with our findings in the rest paragraphs. The revisions are found on pages 37 , lines 653 in the discussion section of the revised manuscript.*

**13)** page 29, line 642: "...and perhaps this is the data..." Don't you know or why are you saying "perhaps"? I recommend to reformulate this and to be more precise.

***Answer***

*We have reformulated the sentence and perhaps is removed. The revision is found on page 39, lines 695-697 in the discussion section of the revised manuscript.*

14) page 30, line 659: "...will be higher water available" <-- more water

*Answer*

*We have replaced higher with more as suggested by the reviewer in the revised manuscript. The revision is found on page 40, lines 713 in the limitation section of the revised manuscript.*

15) page 31, line 678: "...that we are not totally off..." <-- This is colloquial language

*Answer*

Thank you. We have removed the phrase "we are not totally off" and the sentence consisting of the phrase has been revised. The revision is found on page 41, lines 732-734 in the conclusion section 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 poses 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 challenging to quantify to what extent the change will affect the flow patterns, and floods from small rural catchments due to the 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 the level of small catchments, it is therefore beneficial to use a high spatial and temporal resolution climate projections as input to a high-resolution hydrological model. In this study, we used such a model chain to assess the impacts of climate change on the flow patterns, and frequency of floods in small ungauged rural catchments  
20 in Western Norway. We used a new high-resolution regional climate projection, with improved performance regarding to the precipitation distribution, and a regionalized hydrological model (Distance Distribution Dynamics) between a reference period (1981-2011) and a future period (2070-2100). The flow-duration curves for 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  
25 annual flow increases by 16% to 33%. The mean annual maximum floods increase by 29% to 38%,

and floods of 2 to 200-year return periods increase by 16% to 43%. The results are based on the RCP8.5 scenario from a single climate model simulation tailored to the Bergen region in Western Norway, 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  
30 increases our knowledge and understanding of the hydrological impacts of climate change on small catchments in 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  
35 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 vary considerably in different parts of Europe because of changes in large-scale atmospheric circulation or local orographic circulation (Eisenreich et al., 2005, Hattermann et al.,  
40 2007).

Changes in temperature and precipitation, and the shift in winter precipitation from snow to rain play an important role in studying impacts of climate change on the hydrology of a catchment. These changes influence the hydrological regime of a stream, and the most serious and widespread  
45 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 results in increasing mean annual 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 scenario (Hanssen-Bauer et al., 2015). The largest increase in precipitation is mostly expected during the autumn and winter months, which will in turn impact the magnitude and in some cases the seasonality of flood peaks. A climate impact study in Sogn and Fjordane county of Norway showed that flood peaks shift from summer to autumn in the future scenario (2071-2100) (Chernet et al., 2014). Donnelly et al. (2017) studied climate change impacts on European hydrology and found that climate change will strongly affect the hydrological cycle in the regions of Europe where Norway is 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; Blöschl et al., 2019; Madsen et al., 2014; Mallakpour & Villarini, 2015; Rojas et al., 2013). Adverse effects of climate change on river regimes worldwide (Pumo et al., 2016), calls attention to the hydrological impact of climate change study at a local scale.

The projected increase in heavy localized precipitation events increases precipitation-generated local flooding. An increase in local flash floods can cause significant danger, and loss of life and property (Borga et al., 2011, Kundzewicz et al., 2014). Local flash floods usually occur in small catchments (e.g., area less than 50 km<sup>2</sup>). These type of flood events are usually short in duration, but they are usually connected with severe damages (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 by prevailing convective precipitation at hilly or mountainous areas.

A quantitative analysis of the impacts of climate change on the stream flow requires simulations in a hydro-meteorological system. The models on which the simulations are based should adequately represent 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. These models are needed in order to assess the likely effects of climate change, and to propose appropriate adaptation strategies (Baltas, 2007). The results of regional climate impact studies aid in proposing adaptation measures adapted to local climatic, geographic, economic and social conditions (Hattermann, 2009, Krysanova et al., 2008). Investigating the 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).

Assessing the impacts of climate change on hydrology of small ungauged catchments is challenging for the following reasons: unavailability or inadequacy of hydro-meteorological data for calibration of hydrological models, the short response time of the catchments, difficulty in describing local hydrological processes and coarse resolution of climate models. Inadequate process representation in climate models, with coarse spatial resolution (e.g. grid spacing of 9km), results in poor representation of the observed precipitation in small catchments (e.g. area less than 50km<sup>2</sup>) which is inadequate for the assessment of impacts in small 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 meaningful climate impact results for small catchments, it is necessary to use high spatial  
95 and temporal resolutions of projected climate data as forcing in high resolution hydrological  
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  $0.11^\circ$  grid, however a new high-  
resolution regional downscaling with improved representation of local precipitation distribution  
100 for southern Norway is available (Pontoppidan et al., 2018), but has yet to be included in a full  
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  
105 developed and tested. Tsegaw et al. (2019a) calibrated and validated the Distance Distribution  
Dynamics (DDD) hydrological model for forty-one gauged small rural catchments in Norway with  
hourly temporal resolution. For predicting flow in the ungauged catchments, the DDD model  
parameters were regionalized using three different methods of regionalization (multiple regression,  
physical similarity and combined method). The methods were subsequently tested on seven  
110 independent catchments. The findings show that the combined method performs the best of all the  
methods in predicating flow. Even though the DDD model predicted the flow at ungauged  
catchments satisfactory ( $0.5 \leq \text{Kling-Gupta Efficiency} < 0.75$ ), the model underestimates most of  
the observed flood peaks (Tsegaw et al., 2019a). To improve the prediction of observed floods, a  
dynamic river network method has been introduced and implemented in DDD (Tsegaw et al.,  
115 2019b). It is this improved setup that has been used in this study where the general objective was  
to assess the hydrological impacts of climate change on small ungauged catchments using a novel

model chain consisting of a high resolution, bias corrected dynamical downscaled climate scenario, and the improved DDD model. More specifically:

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

## 2. Data and methods

### 125 2.1 Study area

The Bergen area is known for its wet climate. The location is in Western Norway (60N, 5E) with a coastal climate, and a pronounced topography. The annual precipitation for the normal period 1961-1990 was of 2250 mm at the Florida weather station, with precipitation typically occurring 243 days of the year every year (i.e. days with 0.1 mm or more precipitation) (Kristvik and Riisnes, 130 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).

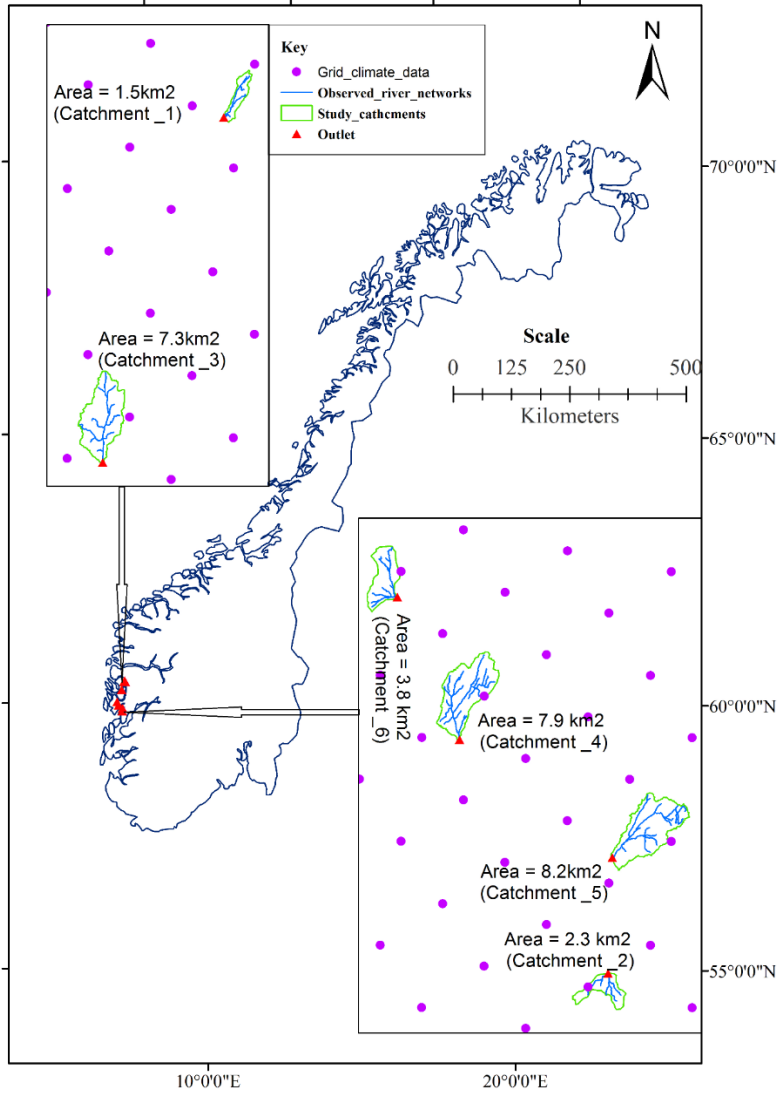
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Floods in the Western part of Norway (where Bergen is located) are mainly caused by heavy rainfall during the autumn season (Roald, 2008). The Norwegian Center for Climate Services report pointed out that a rainfall-dominated floods are projected to increase by almost 60% (with



RCP8.5 scenario ) 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 being fed by small upland catchments (Hanssen-Bauer et al., 2015). Vormoor et al (2015) found that autumn/winter events will become more frequent by 2099, which will lead 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 Western Norway, 50% of the stations show a shift towards occurring floods later in the year by more than +8 days per 50 years.

Six ungauged small rural catchments, located in Western Norway around Bergen city, were used in this study. The catchment descriptors data are taken from <http://nevina.nve.no/> and <http://www.statenskartverk.no/>. The definition of small rural catchments is based on the report by Fleig and Wilson (2013) applying an upper area limit of 50km<sup>2</sup>. The catchments were selected for this 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 (2070-2100). We selected three catchments with bare mountain dominated (>50%) and three catchments with forest dominated (>50%) land uses to include a diverse type of land uses in the study. The locations of the catchments and stream network for each of the catchments are depicted in Fig. 1. The catchment descriptors (CDs) and outlet coordinates are presented in Table 1.



**Figure 1.** Locations of study catchments in Norway

**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 <sub>m</sub>	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 <sub>mr</sub>	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 <sub>r</sub>	1513.2	960.5	2671.2	3061.1	3402.8	1733.3
Catchment area	<i>km</i> <sup>2</sup>	A	1.5	2.3	7.3	7.9	8.2	3.8
Effective lake	%	L <sub>e</sub>	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 <sub>e</sub>	684.6	322.1	314.7	461.5	402.1	466.7
Mean annual precipitation	<i>mm</i>	M <sub>p</sub>	3268.0	2243.0	2500.0	2781.0	2543.0	2644.0
Specific discharge	<i>l s</i> <sup>-1</sup> <i>km</i> <sup>-2</sup>	S <sub>q</sub>	141.0	115.7	91.8	125.6	134.2	110.7
Mean river slope	<i>m km</i> <sup>-1</sup>	R <sub>s</sub>	162.6	266.2	88.4	106.4	118.6	154.9
<b>Outlet location</b>								
ETRS_1989_UTM_Zone_33N coordinate system (m)	Longitude		-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

## 2.2 Climate, topography and land use data

### 165 2.2.1 Climate data and bias correction

The precipitation and temperature data used to drive the hydrological model were 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 RCP8.5 scenario climate projection is unique because of its high  
170 spatial grid resolution of 4 x 4 km. To our knowledge, no other convective permitting, century-long, dynamically downscaled climate projection is available for Norway. Precipitation and temperature data are available with a 3 hours resolution. However, regional models, such as WRF, inherit biases from the boundary conditions used to drive the model. These biases may lead to a misrepresentation of important features in the models, e.g. the known bias of the North Atlantic  
175 storm track (Zappa et al., 2013) leads individual storms into central Europe instead of one a more northern path along the Norwegian coast as the 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.,  
180 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).

185 Bias correction is a commonly used method to address systematic model errors. Many studies  
apply a correction towards observation on variables such 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 constrains the model output, and the use of such has therefore been questioned  
190 (Maraun, 2016; Maraun et 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  
195 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  
200 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.

Bias-correction of the global climate model driving data prior to the dynamical downscaling, lead  
205 to physical consistency in the interior domain, and a potential gain from the increased horizontal  
resolution. The approach showed improved precipitation representation in an Australia (Rocheta  
et al., 2017), and in a North American climate (Wang & Kotamarthi, 2015; Xu & Yang, 2012,

2015) as well as in a 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).

The bias correction was performed following the anomaly approach, available for downloading and thoroughly described in Bruyere et al., (2015). A reference period of 30-years (from 1981 to 2010) was selected for which we calculated the monthly means of ERA-Interim for each month of January to December, resulting in 12 monthly mean terms (Eq. 1). Similarly, the 12 monthly means were calculated from the 6-hourly NorESM1-M input data for the reference period, and subsequently the 6-hourly input data was separated into a monthly mean term, and the deviation from the monthly mean term (Eq. 2). For the future period, the 6-hourly NorESM1-M input data was separated 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 (Eq. 2). The new bias corrected (*BC*) NorESM1-M data were then calculated by substituting the NorESM monthly mean with the ERAI mean (Eq. 3), which is equivalent to the summation of the monthly mean from the reanalysis product and the NorESM1-M deviation term (Eq. 4).

$$\overline{ERAI}_{ref} = \frac{\sum_{n=1}^{n=k} ERAI_{m,n}}{k} \quad (1)$$

where  $m$  is a month from January to December,  $n$  is the number of time steps in a month ( $n = 1, 2, 3, \dots, k$ ),  $k$  is the total number of time steps in a month.

$$NorESM = \overline{NorESM}_{ref} + NorESM' \quad (2)$$

$$NorESM_{BC} = NorESM - \overline{NorESM}_{ref} + \overline{ERAI}_{ref} \quad (3)$$

230

$$NorESM_{BC} = \overline{ERAI_{ref}} + NorESM' \quad (4)$$

235

Here, the mean terms ( $\overline{ERAI_{ref}}$  and  $\overline{NorESM_{ref}}$ ) were from the 30-year reference period and the deviation term ( $NorESM'$ ) was the deviation from the reference period means. Opposed to the pseudo global warming method, this approach ensured that the forcing files of our experiment retained the sub-monthly variability from the climate model, but with an adjusted climatological mean for longer time scales.

240

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 performed. Based on this finding, 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.

### 2.2.2 Topographical and land use data

245

The DDD model parameters, which do not need regionalization, were derived from analysis of topographical and land use data of the catchment using GIS. The source of the topography and land use data was the Norwegian Mapping Authority (<http://www.statenskartverk.no/>). The 10 x 10 m DEM, the river network and the 1: 50 000 scale land use data were retrieved and used in this study. The DEM was 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 was further used to determine the distance distributions of hill slopes and river networks as needed by DDD.

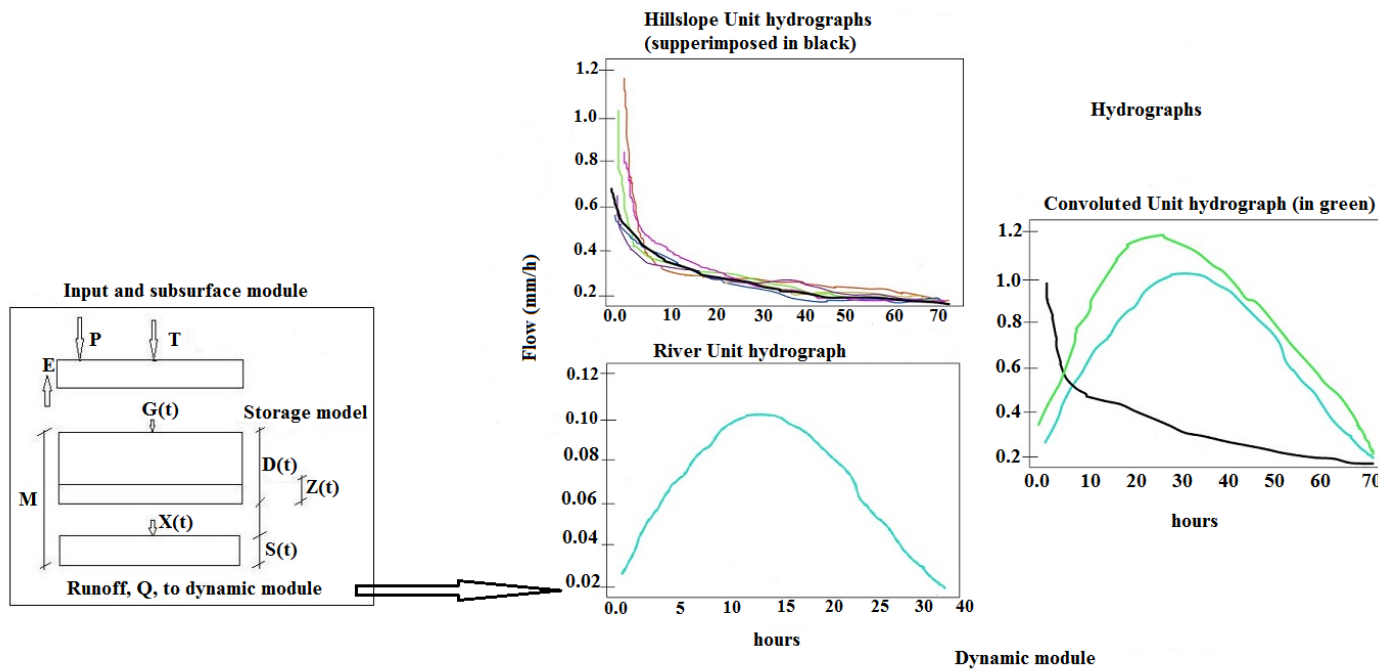
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## 2.3 DDD hydrological model

### 2.3.1 General description of the model

The Distance Distribution Dynamics (DDD) hydrological model was 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 a semi-distributed conceptual model and it is applicable for catchments ranging from small (e.g. 1km<sup>2</sup>) to large (e.g. 5000km<sup>2</sup>), and temporal resolutions ranging from low (e.g. daily time step) to high (e.g. hourly time step). 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 a runoff recession analysis. The DDD model applies the distribution of distances between points in the catchment and their nearest river reach (distance distributions of a hillslope) as the basis for describing the flow dynamics of the hillslope. The distribution of distances between points in the 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 GIS and recession analysis respectively (Skaugen and Mengistu, 2016, Skaugen and Onof, 2014). Figure 2 shows the structure of the DDD model.





275 **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.

### 2.3.2 Dynamic river network method in DDD

Stream networks in a catchment expand and contract as the catchment wets and dries, both seasonally, and in response to individual precipitation events. This dynamic of stream networks gives important information to the pattern, and process of runoff generation in the catchment.

285 Dynamic river networks, and hence dynamic overland unit hydrographs has been introduced and implemented in the DDD model in order 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 dynamic  $D_m$  from the relation between the upstream critical supporting area ( $A_c$ ) i.e. 290 the area needed to initiate and maintain streams and  $D_m$  using GIS and python script as shown in Eq.(5). The coefficients (a and b) are estimated for the study catchments and presented in Table 2. The calibration parameter of the dynamic river network routine in DDD is the critical flux ( $F_c$ ) and is estimated by regional regression in this study.

$$D_m = aA_c^b \quad (5)$$

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

Catchment	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

### 2.3.3 Model parameters and regionalization

The DDD model parameters are divided into three main groups. The first group contains the parameters estimated by recession analysis from observed flow data (for gauged catchments) or through regionalization for ungauged catchments (appendix 1). The second group contains the parameters estimated by model calibration (for gauged catchments) against observed discharge or by regionalization (for ungauged catchments) (appendix 2). The third group contains the parameters estimated from digitized geographic maps using GIS (appendix 3). In addition, the snow routine in DDD has two parameters estimated from the spatial distribution of observed precipitation data (Skaugen and Weltzien, 2016). The shape parameter ( $a_0$ ) and the decorrelation length ( $d$ ) of the gamma distribution of the snow and the snow water equivalent (SWE) are estimated from a previous calibration using 84 catchments in Norway (Skaugen et al., 2015). As this study focuses on ungauged catchments, it was not possible to conduct calibration and recession analysis. The model parameters in need of calibration and recession analysis were therefore derived through a 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), regionalized DDD model parameters with hourly resolution was used (Tsegaw et al., 2019a). In the combined method of regionalization, the recession parameters and critical flux were estimated using multiple regression between model parameters and CDs, and the parameters in need of calibration (all in appendix 2) were estimated using the physical similarity method. The parameters of the model needing regionalization are shown in appendix 1 and 2 (the bottom 5 in appendix 1, and all in appendix 2). The CDs of the study catchments, used to get the DDD model parameters through regionalization, are presented in Table 1.

320 **2.4 Impact study**

The precipitation and temperature data were extracted from the 4 x 4 km and 3 hourly resolution climate model. The climate data were then used to force the DDD model to simulate flow, actual evapotranspiration, and snow water equivalent (SWE) both for the reference and the future periods.

325 A total of 30 hydrological years (1<sup>st</sup> of September to 31<sup>st</sup> of August) were used for both periods in the impact study. We have analyzed changes in the following indicators used to describe the climate change impacts.

- 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.
- 330 iii) The annual 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-year

Changes are computed by Eq. (6) using the magnitudes of hydroclimatic variable for the reference and the future periods.

335

$$Change\ in\ x(\%) = \left( \frac{Future\ value\ of\ x - Reference\ value\ of\ x}{Reference\ value\ of\ x} \right) * 100 \quad (6)$$

where  $x$  is any hydroclimatic variable.

### 2.4.1 Changes of hydroclimatic variables

The 3-hourly precipitation and temperature data, extracted from the climate model, were analyzed using an R-script to quantify the changes in the mean annual values **between** the reference and future period. **The 3-hourly time series precipitation, temperature and discharge data were**  
345 **converted to annual series which was further analyzed in order to obtain the mean annual values.**

Seasonal mean flow data was also estimated for the reference and the future periods i.e. winter, spring, summer, and autumn in order to assess the changes in the seasonal mean flows. The annual maximum SWE was selected from each hydrological year and averaged for the reference and the  
350 future periods to get the mean annual maximum SWE for the two periods. The annual actual evapotranspiration was 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.

### 355 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. It shows the flow characteristic of a stream throughout a range of flow, without regard to the sequence of occurrence (Searcy, 1959). The changes in stream flow variability over a **hydrologic** year between the reference and the future periods was  
360 analyzed. The changes of floods (between 0% and 5% exceedance) and the median flows (flows which are exceeded by 50% of the time) were analyzed in this study. The formula to calculate the probability of exceedance is given by Eq. (7).

$$p = 100 * K / (n + 1) \quad (7)$$

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

365  $K$  = the ranked position on the listing (dimensionless).

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

### 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  
370 of annual winter/spring (WS), and fall stream flow were analyzed using the center of volume (CV)  
date (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 a  
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  
375 the 3-hour flow data (simulated for the reference and future periods), the mean 3-hour flow value  
for the 30 years in both periods was calculated. Using the mean 3-hour flow value, the seasonal  
center of volume dates for the winter/spring (1 January to 31 May) and fall (1 October to 31  
December) was calculated.

### 380 2.4.4 Changes in the maximum flows and flood frequency

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

The number of 3-hour floods above a certain threshold gives a general overview on the impacts  
385 of climate change on the flood risk in small catchments. Accordingly, we 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 of the reference period.

To assess the magnitude of a flood with a given probability, the flood frequency methods must  
390 be applied. A flood frequency analysis is important for flood hazard mapping, for which a flood  
of a certain return period (e.g. 200-year 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 of the  
reference (1981 – 2011) and future period (2070 – 2100). In this study, the Gumbel distribution  
395 (Bhagat, 2017, Shaw, 1983) was used to model the annual maximum series. The Gumbel  
distribution was selected because it has been widely applied in studies of climate change  
impacts on floods in Europe (Dankers and Feyen, 2008, Veijalainen et al., 2010).

### **3. Results**

#### **400 3.1 Regionalized DDD model parameters**

The results of the model parameters obtained after the regionalization are presented in Table 3  
for all study catchments. The parameters and possible ranges of values are presented in  
appendix 4.

405

**Table 3:** Values of DDD model parameters estimated from regionalization for the study catchments.

Model parameters needing regionalization	Catchments					
	Cat_1	Cat_2	Cat_3	Cat_4	Cat_5	Cat_6
Gshape	2.32	1.83	1.98	2.087	1.961	2.032
Gscale	0.04	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

### 3.2 Changes in hydroclimatic variables

410 The simulation results of the climate and hydrological models were further analyzed to quantify the changes in the hydroclimatic variables. The mean annual precipitation, temperature, evapotranspiration, flow, and the mean autumn and winter flows increase for all the study catchments in the future period, compared to the reference period. The mean spring flow increases in five of the catchments and decreases in one of the study catchments. The mean summer flow decreases for five of the 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 %, and the mean annual temperature rises by 3 °C to 3.3°C. The mean annual flow increases by 17% to 33%. The decrease in the mean summer flow ranges between 7% to 35% and the increase was 4% in only one of the study catchments. The mean winter flow increases by an average of 127% (ranging between 41% to 256%). The mean spring flow increases by

415

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4% to 100% for five of the catchments and a 1% decrease in one catchment. The mean autumn flow increases by an average of 37% (ranging from 21% to 43%). The results of changes of in 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 425 catchments. Mean 3-hourly flow of the study catchments are shown in Fig. 3 for the reference and the future periods.

**Table 4:** Changes in mean annual temperature, precipitation, maximum snow water equivalent (SWE) and evapotranspiration for all the study catchments using bias corrected NorESM1-M (r1i1p1) global climate model, WRF regional climate model and RCP8.5, and DDD model.

<b>Hydro-meteorological indicator</b>	<b>Unit</b>	<b>Change in indicator</b>
<b>Cat_1</b>		
Mean annual precipitation	mm	22 %
Mean annual temperature	°C	3.3 °C
Mean annual maximum SWE	mm	-78 %
Mean annual evapotranspiration	mm	63 %
<b>Cat_2</b>		
Mean annual precipitation	mm	24 %
Mean annual temperature	°C	3.1 °C
Mean annual maximum SWE	mm	-48 %
Mean annual evapotranspiration	mm	67 %
<b>Cat_3</b>		
Mean annual precipitation	mm	24 %
Mean annual temperature	°C	3.2 °C
Mean annual maximum SWE	mm	-50 %
Mean annual evapotranspiration	mm	43 %
<b>Cat_4</b>		
Mean annual precipitation	mm	20%
Mean annual temperature	°C	3.2 °C
Mean annual maximum SWE	mm	-56 %
Mean annual evapotranspiration	mm	132 %
<b>Cat_5</b>		
Mean annual precipitation	mm	22 %
Mean annual temperature	°C	3.2 °C
Mean annual maximum SWE	mm	-49 %
Mean annual evapotranspiration	mm	81 %

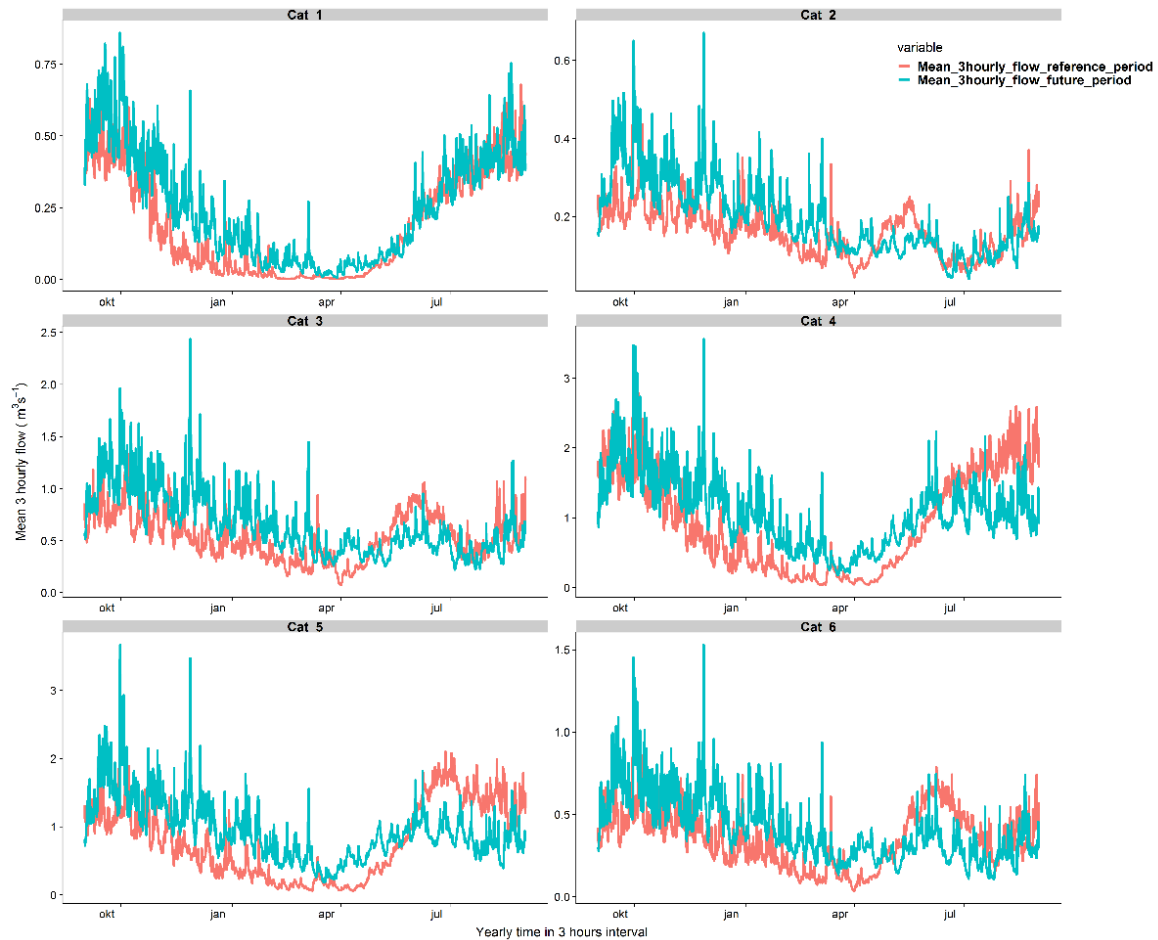
**Cat\_6**

Mean annual precipitation	mm	20.0 %
Mean annual temperature	°C	3.0 °C
Mean annual maximum SWE	mm	-63.0 %
Mean annual evapotranspiration	mm	92 %

430

**Table 5:** Changes in percentage of mean annual flow, and seasonal flows for the study catchments.

<b>Hydrologic indicator (flow)</b>	<b>Change in indicator (%)</b>	<b>Hydrologic indicator (flow)</b>	<b>Change in indicator (%)</b>
<b>Cat_1</b>		<b>Cat_4</b>	
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
<b>Cat_2</b>		<b>Cat_5</b>	
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
<b>Cat_3</b>		<b>Cat_6</b>	
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



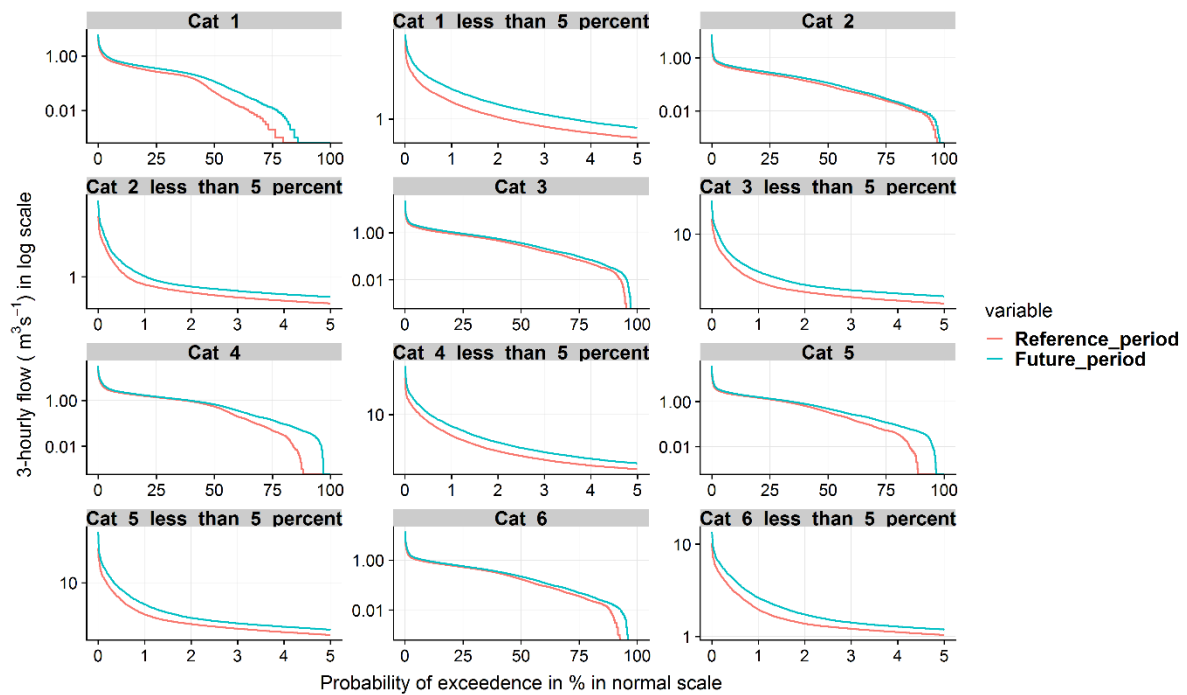
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**Figure 3.** Yearly mean 3 hourly hydrographs of the study catchments for the reference and future periods.

### 3.3 Changes in flow duration curves

440 The results of the study show that changes in the flow duration curves (FDCs) values are positive for all the flow **conditions in all the study catchments**. For all catchments, the top 5% of flows in the future period were higher than the flows in the reference period by 8% to 62%. In the future period, the median flows increase by 24% to 140% (the highest value is for catchment 1 and the lowest value was for catchment 4). Figure 4 shows the FDCs for both

445 periods for the probability of exceedance less than 5% and 100% for all the study catchments.



**Figure 4:** Flow duration curves (FDCs) of the 3-hourly flow for the six study catchments for the reference and the future periods with the probability of exceedance less than 5% and 100%.

### 450 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 occurred earlier in the future period (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 WSCV dates and mean fall CV dates for all the study catchments.

455

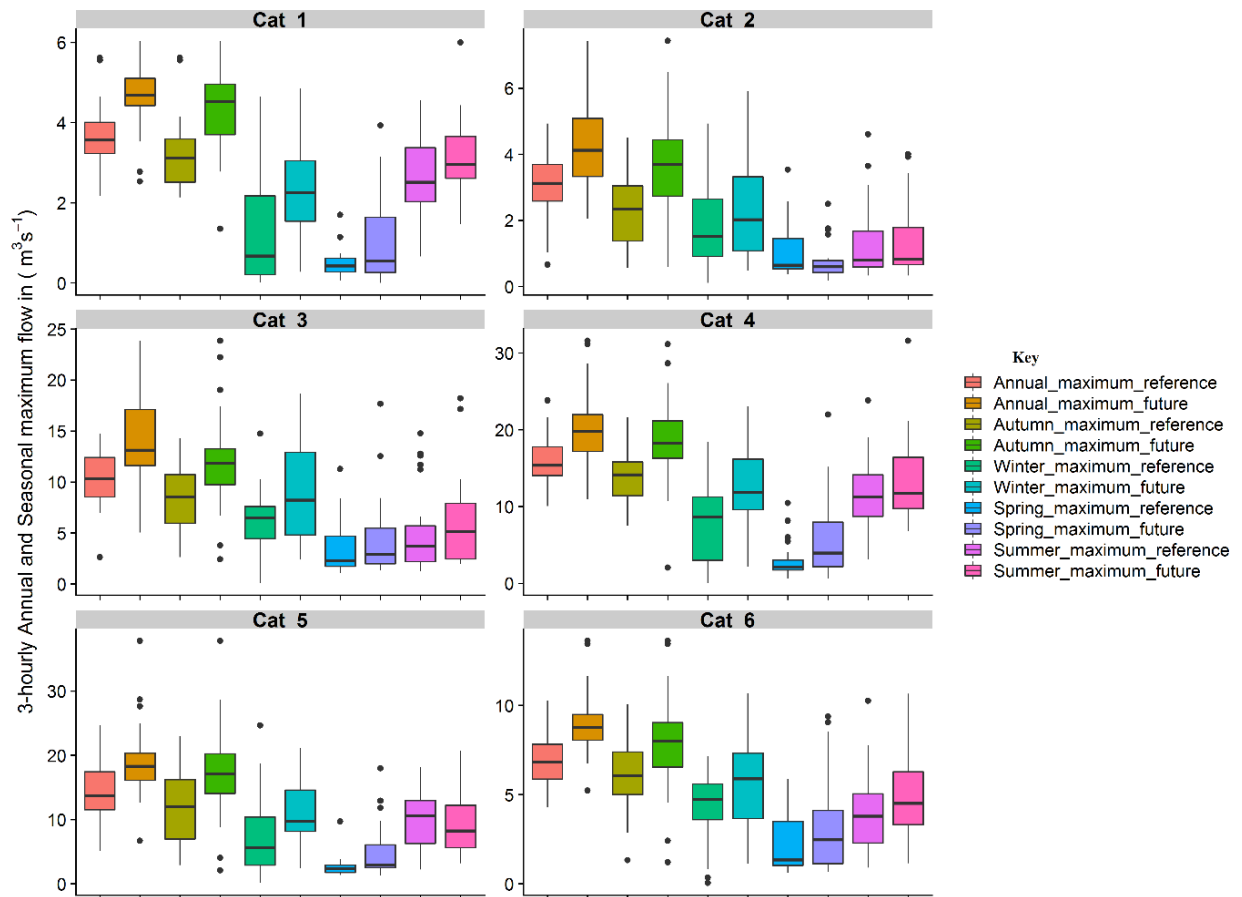
### 3.5 Changes in the maximum flows and flood frequency

#### 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 by 29% to 38% across all the study catchments. The mean seasonal maximum flows also show an increase in all seasons

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(1 % to 118%), and all catchments except for the spring season of catchment 2 (reduction of 29%) as shown in Table 7. The median of the annual and seasonal maximum flows increases for all catchments except for the 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.



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

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

<b>Annual and Seasonal maximum flows</b>	<b>Change in indicator (%)</b>	<b>Annual and Seasonal maximum flows</b>	<b>Change in indicator (%)</b>
<b><i>Cat_1</i></b>		<b><i>Cat_4</i></b>	
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
<b><i>Cat_2</i></b>		<b><i>Cat_5</i></b>	
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
<b><i>Cat_3</i></b>		<b><i>Cat_6</i></b>	
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

475 The number of 3-hours floods, exceeding the minimum annual maximum floods 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.

**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	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	21	133
<i>Cat_2</i>	58	99	71
<i>Cat_3</i>	38	64	70
<i>Cat_4</i>	9	15	71
<i>Cat_5</i>	22	36	62
<i>Cat_6</i>	7	13	90

485 **3.5.2 Changes in flood frequency**

The study results, from the six ungauged small rural catchments, show that there will be an increase in floods with a return periods of 2 to 200-year in the future period. The floods are expected to increase by 16% to 43%. Table 9 shows the changes of 2 to 200-year floods for all the study catchments.

490

**Table 9:** Changes of floods with return periods of 2 to 200 year between the future and reference periods using Gumbel’s Extreme Value Distribution for all study catchments.

Return period (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

## 4. Discussion

### 495 4.1 Regionalized DDD model parameters

The physical similarity assessment result, 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. This result is an evidence that the regionalization method used in this study is plausible.

### 500 4.2 Hydrological impacts of climate change

#### 4.2.1 Changes of hydroclimatic variables

Generally, the findings of the increase in precipitation and temperature for the study catchments are in the ranges of the **increases** 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  
505 some of the catchments were above or below the prediction interval of the report. This differences  
for some catchments was 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).

510

The NCCS report shows that the median projections **for changes** 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 3.7°C and 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  
515 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.

520

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 **2070s**. This result can be comparable with our findings  
525 i.e. the increment could increase by 17% to 33 % **between 2070 - 2100**. **The increase in mean**

annual flow is the result of an increase in the mean annual precipitation and temperature (Table 4).

The increase in the mean annual temperature results in an increase of water loss by evapotranspiration. However, the mean annual 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 could decrease up to 1% and increase up to 17% for western Norway (where the study catchments are located) by 2100, and our result shows that the increase is higher than the increase in the report for four of the study 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 values in the report may lead to differences.

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 for the increase are projected increase in the precipitation and temperature during the autumn and winter seasons. The increase in the mean annual flows is mainly the result of an increase in mean winter flows 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 of the catchments 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  
550 in temperature may not result in high evapotranspiration to reduce the mean summer flow at the  
high-elevation catchment.

Similar results are found in other hydrological assessments of the Bergen region. Previous studies  
of the water resources under climate change project higher temperatures and increased annual  
555 precipitation in the Bergen region for the 2071-2100 future period under the RCP8.5 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  
560 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 flows increase by 15% to 42% and by 5% to 36% respectively by 2100. The report also  
predicts that the mean spring flow will decrease up to 9% and will increase up to 17%, and the  
565 mean summer flow will decrease by 13% to 28% by 2100. The findings of our 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. In our study, a reduction in mean summer flows was higher than the  
reduction in the report in four catchments. The findings of this study show that the increase in the  
570 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 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) pointed out that the summer flow in Norway is projected to be reduced and supports the findings of our study.

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 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 in temperature for all study catchments in the future period, and the increase resulted in rain to take the snow share which gives rise to the reduction of mean annual maximum SWE at all the study catchments.

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#### **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  
595 future FDCs are higher than the FDCs 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.

#### **600 4.2.3 Changes in WSCV and fall CV dates**

The results for the mean winter/spring center of volume date (WSCV) showed that WSCV will  
occur earlier. While the mean fall CV date came to 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  
605 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. This condition makes the future bulk of high flows to occur towards the  
610 end of a year which will result in 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

#### 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 the seasonal maximum flows (Table 7 and 8, and Fig.5) for all the study catchments except for the spring season for catchment 2. Most (15 – 23 of the 30 annual maximum floods) of the maximum annual flows occur during the autumn period (1<sup>st</sup> September to 30<sup>th</sup> of November) and therefore much of the contribution for the increment of the mean and median annual maximum flows stems from the autumn season (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 will 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 the mean annual maximum flows (floods) show an increase of 29% to 38% is supported by the study of 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 in order to assess the likely changes in hydrological floods between a reference period (1960 – 1990) and two future periods (2021-2050) and (2071 - 2100), in 115 catchments distributed throughout Norway. Their results showed that western regions of Norway are associated with the largest percentage increases in the magnitude of the mean annual floods (greater than 20%). Lawrence and Hisdal (2011) also pointed out that the increase in autumn and winter rainfall increases the magnitude of peak flows (floods) during these seasons throughout Norway. For areas already dominated by autumn and winter floods, the projected increases in flood

magnitude are large. Lawrence and Hisdal (2011) findings support the findings in this study i.e. the maximum increases in floods magnitude are expected to happen in autumn and winter seasons (Table 7 and Fig.5).

The yearly average number of 3-hour floods values, which are greater than the minimum of the annual maximum floods in the 30 years of the reference period, increases. The yearly average number of such floods increase between 62% and 133% across all study catchments as presented in Table 8. The results show that there will be a greater number of 3-hour floods in the future period than the reference period and this could increase flood risks at the infrastructure constructed downstream of small ungauged rural catchments in Bergen region of west Norway. European Environmental Agency(2004b), in: Alcamo et al. (2007) found that the risk of floods will increase in northern Europe (e.g. Norway) which supports our finding of increase in the risk of floods. The center for International Climate Research (<https://cicero.oslo.no>) predicts that Western Norway will experience more heavy rain and flooding in the future. Our finding confirms their predictions.

#### 4.3.2 Changes in flood frequency

For all return periods, the mean increases of floods were between 31 % and 32% while the median increases were between 30% and 34%. The increase in the 2 to 10-year floods is more than 20% for all study catchments, and the 20 to 200-year floods increase is greater than 20% for five of the study catchments. The 50-year flood will increase by 18% to 40 % in the future periods. The results also show that the increase in the 200-year floods is greater than 30% for four of the six

study catchments (1 catchment between 10% -20%, 1 catchment between 20% -30%, 2 catchments  
660 between 30% - 40% and 2 catchments between 40% and 50%).

Beldring et al. (2006) studied the percentage change in the mean annual floods and the 50-year  
floods in four catchments in Norway between 1961-1990 and 2070-2100 and found that moderate  
to large increases are expected (one of the study catchments is in Western Norway (Viksvatn in  
665 Gaular)). Beldring et al. (2006) finding supports the findings in this study. Lawrence and Hisdal  
(2011) have found that the projected increase of the 200-year floods exceeds 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 EURO-  
CORDEX regional climate projections data to force HBV hydrological model for assessing  
670 possible effects of climate change on floods in 115 catchments in Norway for two future periods  
(2031-2060 and 2071-2100). The assessment result shows that the minimum increase in the 200-  
year flood, for catchments less than 100km<sup>2</sup> at Hordaland county (where study catchments are  
located), is 20% which is generally in agreement with our findings i.e. five of the six catchments  
show greater than 20% increase for 200-year floods.

675  
Lawrence (2016) showed that the increase in the 200-year 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 200-year flood frequency. Of the 115 catchments used in the study for the whole Norway,  
10 of them are in the Hordaland county. With RCP4.5 scenario, eight of the ten catchments showed  
680 less than 20 % increase ( 1 catchment a decrease, 2 catchments an increase 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 RCP8.5 scenario, 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 change of less than 0% and 2 catchments an increase between 11% - 20%). Generally, our finding with RCP8.5 is similar to the Lawrence (2016) finding with RCP8.5 except that our finding shows an increase higher than 40% for two of the study catchments.

690 The main differences between this present study and Lawrence (2016) study are: the number and types of climate models, RCPs, the catchment sizes and temporal resolution. The comparisons of the increase in floods 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 were ranging from 6km<sup>2</sup> to 15449km<sup>2</sup> and used 10 global-regional models with RCP8.5 and RCP4.5. The temporal resolution, used in the Lawrence (2016) study, was daily and this daily data has been bias corrected after the GCM-RCM chain. Changes in floods, higher than 40% for some catchments in our findings, are related with the differences in the climate models, in the bias correction method, in the temporal resolutions used, in the hydrological models used, 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.

#### 4.4 Limitations

705 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 method developed for 1 hour (Tsegaw et al., 2019a) to estimate the DDD model parameters for the 3-hours simulation. DDD model parameters like degree hour factor for evapotranspiration (Cea) and degree hour factors for snow melt (Cx) are sensitive to the temporal resolution.

710 However, the same uncertainty is present both in the reference and future periods. The second limitation is related to the simple degree evaporation model used in the DDD model. Table 4 shows large changes in actual evapotranspiration. The large change 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; however, there is a limitation with the simple

715 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 large change of actual evapotranspiration between the reference (1981-2011) and the 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

720 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 RCP8.5 scenario. Thereby, we are not able to capture the

725 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.

730

This paper represents 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 our findings are supported by the results of other studies except for a few differences.

735

Therefore, our findings can give a useful addition to the current understandings of the effects of changing climate on the west coast of Norway. 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.

740

## 5. Conclusion

In this study a newly developed bias corrected dynamical downscaling product as input for the improved DDD model to investigate the impact of climate change in small ungauged catchments in Western Norway. The results show that there will be an increase in the mean annual flow for the future period (2070-2100). 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 flow decreases for all the study

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catchments except one. The future flow duration curves are higher than the flow duration curves  
750 of the reference period for all study catchments for all probability of exceedances. The median  
flow (flows which are exceeded 50% of the time) increased by 24% to 140%. The FDCs of all  
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.

755 There will be an increase in the mean annual floods, and floods of 2 to 200-year return period in  
the future period. The mean annual maximum floods increase by 29% to 38%. This study gives  
clear indication that the projected increase in flood frequencies is high (e.g. 200-year floods greater  
than 40%) in small catchments around Berge area in Western Norway. Such catchments will be  
more vulnerable to flood risk under the projected future climate. The high-resolution regional  
760 climate model with a novel bias correction method improves the knowledge and understanding of  
climate change impacts on a hydrology of small catchments in Western Norway. However, it is  
important to conduct further research to address the limitations of this study prior to conducting  
flood risk assessment, and planning flood risk management strategies as a national strategy for  
climate change adaptation.

765  
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  
770 suggested as a venue for further work in order to account for uncertainties in the RCP scenarios

and 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  
 1085 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 $\lambda$	Regression	Positive real number
Gscale	Scale parameter of $\lambda$	Regression	Positive real number
GshInt	Shape parameter of $\Lambda$	Regression	Positive real number
GscInt	Scale parameter of $\Lambda$	Regression	Positive real number
Fc	Critical flux	Regression	$\text{m}^3/\text{hour}$

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

	<b>Parameters</b>	<b>Description of the parameter</b>	<b>Method of estimation</b>	<b>Unit</b>
1095	Pro	Liquid water in snow	Regionalization (poolig group)	fraction
	Cx	Degree hour factor for snow melt	Regionalization (poolig group)	mm °C <sup>-1</sup> hour <sup>-1</sup>
	CFR	Degree hour factor for refreezing	Regionalization (poolig group)	mm °C <sup>-1</sup> hour <sup>-1</sup>
	Cea	Degree hour factor for evapotranspiration	Regionalization (poolig group)	mm °C <sup>-1</sup> hour <sup>-1</sup>
1100	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

<b>Model parameters needing regionalization</b>	<b>Method of regionalization</b>	<b>Possible ranges of values</b>
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