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Impacts of climate change on drinking water quality in Norway

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ABSTRACT

Climate change will lead to higher temperatures, increased precipitation and runoff, as well as more intense and frequent extreme weather events in Norway. More extreme rainfall and increased runoff are historically associated with higher concentrations of indicator bacteria, colour and turbidity in raw water of Norwegian waterworks. Regional information about the risk for drinking water deterioration by the end of the century is essential for evaluating potential treatment capacity upgrades at the waterworks. We combined locally downscaled future climate scenarios with historical associations between weather/runoff and water quality from a wide spread of waterworks in Norway. With continued climate change, we estimate higher concentrations of water quality indicators of raw water by the end of the century. The water quality is estimated to deteriorate mainly due to the projected increase in rainfall, and mainly in the Western and Northern parts of Norway. While large waterworks seem to be able to adapt to future conditions, the degradation of raw water quality may cause future challenges for the treatment processes at smaller waterworks. Combining these results with further studies of treatment effects and microbial risk assessments is needed to ensure sufficient treatment capacities of the raw water in the future.

Key words: climate change, drinking water quality, indicator bacteria, Norway, rainfall, runoff

HIGHLIGHTS

- Associations between weather/runoff and water at Norwegian waterworks were combined with local climate scenarios for the first time.
- Higher concentrations of water quality indicators of raw water in Norway in the future.
- The future increase in rainfall causes decreased raw water quality in the North and West of Norway.
- Decreasing raw water quality may cause challenges for the treatment processes of small waterworks

INTRODUCTION

In Norway, climate change will lead to higher temperatures, increased precipitation and runoff, as well as more frequent extreme weather events (Hanssen-Bauer *et al.* 2015). In addition, with higher temperatures, rainfall patterns are expected to shift towards more frequent or more intense extreme precipitation (Meehl *et al.* 2007). From 1900 to 2014, the annual mean temperature has already increased by approximately 1 °C (Hanssen-Bauer *et al.* 2015). This observation is associated with increased runoff in winter and spring, and earlier snowmelt. The annual precipitation in Norway has increased by approximately 18% during the same period, with most of the increase occurring after the late 1970s. Heavy short-duration rainfall has increased both in intensity and frequency in recent years (Sorteberg *et al.* 2018).

The observed changes in the Norwegian climate are estimated to continue into the future (Hanssen-Bauer *et al.* 2015). Climate model projections based on a high scenario indicate an increase in the annual mean temperature for Norway of 4.5 °C and an increase in the annual precipitation of 18% by the end of this century. Following the increasing precipitation, the intensity of rainfall-induced floods is also expected to increase (Lawrence 2020). Higher temperatures are likely to lead to a shift towards earlier spring floods and increased possibility for late autumn and winter floods (Beldring *et al.* 2008). These changes in weather and flood patterns may threaten the quality of the Norwegian drinking water.

Extreme weather conditions have long been associated with water quality impacts and associated waterborne diseases (Whitehead *et al.* 2009; Delpla *et al.* 2009; Khan *et al.* 2015; Young *et al.* 2015). Heavy rainfall and runoff, floods, cyclones, droughts, heatwaves, extreme cold and wildfires may all affect water catchments, storage reservoirs, water treatment processes or distribution systems, with potential impacts on the quality of drinking water (Khan *et al.* 2015). Source waters of drinking water may be impacted by increased concentrations of suspended material, organic matter, nutrients, inorganic substances and pathogenic microorganisms (Whitehead *et al.* 2009; Khan *et al.* 2015; Young *et al.* 2015).

The surface waters are particularly vulnerable to changes in temperature, heavy rainfall and floods. Extreme precipitation and runoff events as well as high temperatures may lead to a higher density of microorganisms in water bodies and increase the risk of waterborne disease (Kistemann *et al.* 2002; Hunter 2003; Guzman Herrador *et al.* 2016). The increase in rainfall-induced flooding may also increase human exposure to waterborne pathogens (Kelman 2011). As most of the Norwegian drinking water is obtained from surface water, the Norwegian drinking water may be especially sensitive to the increasing events of extreme precipitation and floods. Ageing drinking water distribution systems and sewage systems will be particularly vulnerable to flooding. Many infectious microorganisms are sensitive to climatic conditions. These factors together will increase the risk and burden of waterborne illnesses.

A recent study shows evidence of associations between weather events and raw water quality in Norway (Guzman Herrador *et al.* 2021). Increased amounts of rain and runoff were associated with increased levels of *Escherichia coli* (*E. coli)*, coliform bacteria, intestinal enterococci, colour and turbidity in raw water throughout the entire year. In raw water, increased maximum temperature was not significantly associated with increased or decreased levels of any of the outcomes throughout the entire year, however, was associated with an increase in coliform bacteria, *E. coli*, intestinal enterococci, and turbidity in winter, and turbidity in spring.

Norway, with its elongated shape and highly diverse topography, has a climate that varies substantially from region to region. In order to evaluate potential upgrades of the treatment capacity at the waterworks, there is a need for regional information about the risk of drinking water deterioration in the future. Therefore, to investigate potential future changes in drinking water quality, known historical associations between weather/runoff and water quality from a geographically wide distribution of Norwegian waterworks must be combined with future climate scenarios that are downscaled to local levels. This has so far not been done.

In this study, we combine the recent associations found in Guzman Herrador *et al.* (2021) with locally downscaled future climate projections in order to estimate regional changes in raw water quality in Norway by the end of the century.

METHODS

Historical associations between weather and raw water quality

We used the associations between weather and raw water quality which were calculated by Guzman Herrador *et al.* (2021). In their study, the water quality indicators coliform bacteria, *E. coli*, intestinal enterococci, colour and turbidity were first collected from 26 of the largest Norwegian waterworks for the period 2006–2014. These were received as weekly averages. For each water work intake point, four weekly averaged observed meteorological and hydrological data (daily maximum temperature (°C), accumulated daily rainfall (mm) and runoff (mm)) were combined with the succeeding week of water quality data for raw water. Finally, mixed-effects linear regression models were run for all water work intake points, as described in Guzman Herrador *et al.* (2021). The resulting associations were stratified by four seasons (winter: December–February, spring: March–May, summer: June–August and autumn: September–November).

Meteorological and hydrological future climate data

For future values of daily maximum temperature, daily accumulated rainfall and runoff, we used post-processed climate projections derived from global climate models (GCMs). The future projections are based on results from the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (Cubasch *et al.* 2013). In this study, one of the IPCC emission scenarios, the so-called 'Representative Concentration Pathways (RCPs)', is used: RCP8.5 (van Vuuren *et al.* 2011). RCP8.5 represents the highest scenario, referring to a future with continuously increasing greenhouse gases. As a precaution, the government demands the work on climate adaptation to consider high alternatives from the national climate projections when consequences of climate change are assessed (Miljøverndepartementet 2013).

GCMs generally operate on a horizontal grid size of 100×100 km^2, which is too coarse to resolve mesoscale phenomena that are important for Norway and its climate. For regional climate impact studies, the model projections are further downscaled by regional climate models (RCMs). The Euro-CORDEX initiative (https://www.euro-cordex.net/) offers a comprehensive database of climate projections with different downscaled GCM/RCM combinations. An ensemble of 10 Euro-CORDEX model runs with a spatial resolution of $12\times12\,\mathrm{km}^2$ was used in this study (Jacob *et al.* 2014). Despite the finer spatial resolution, the climate projections for Norway generally show significant temperature and precipitation biases. A post-processing of the $12\times12\,\mathrm{km}^2$ RCM outputs is therefore necessary. The daily temperature and precipitation values were first interpolated to a $1\times1\,\mathrm{km}^2$ grid. The observation-based datasets, which also have a 1 km resolution, were used for the bias-adjustment procedure which removed systematic biases in simulated values relative to the observed data. For further details of this procedure and the overview of the model ensemble used, see Wong *et al.* (2016). Runoff was then simulated by a precipitation-runoff model with bias-adjusted temperature and precipitation as input data.

Our model ensemble consists of 10 datasets of future projections of daily maximum temperature, daily accumulated rainfall and runoff under the RCP8.5 scenario. These simulation data were collapsed to the yearly median of each of the variables (daily maximum temperature, daily accumulated rainfall and runoff) and were then used as described below in the section ‘Analyses of future changes in water quality’. Control runs from the models cover the period 2006–2014, whereas for the future analyses, we used projections for the period 2071–2100.

Analyses of future changes in water quality

After fitting the mixed-effects linear regression models using the real (observed) data to obtain the associations between meteorological/hydrological data (daily maximum temperature, daily accumulated rainfall and runoff) and water quality data (Guzman Herrador *et al.* 2021), we used the associations ‘rainfall affecting water quality’, ‘runoff affecting water quality’, ‘maximum temperature affecting water quality’ as well as future predicted exposures to estimate the future changes.

The modelled meteorological and hydrological climate data from 2006–2014 to 2071–2100 were used as exposures to the linear regression models from Guzman Herrador *et al.* (2021) to obtain predictions of the raw water quality in 2006–2014 and 2017–2100. These predictions were then aggregated to the yearly level. For each waterwork and climate projection, the predicted multiplicative increase in year X from 2006 to 2014 was calculated as: predicted value in year X/predicted mean in 2006–2014.

For each waterwork, climate projection and year from 2071 to 2100, 1,000 data points were resampled from the original data of water quality indicators, maximum daily temperature, daily accumulated rainfall and runoff used to fit the respective linear regression model and multiplied by the multiplicative increase from 2006 to 2014. We then estimated the 99th percentile in this new simulated dataset for each of the waterworks in order to study the changes in extreme concentrations of water quality indicators.

For this study, Norway was divided into three geographical climate regions: West, East and North, and we allocated each waterwork to its region. Then to report regional values, we used the mean of the 99th percentiles of the waterworks allocated to each region.

RESULTS

Due to future changes in rainfall, we estimated markedly higher future levels of water quality indicators with statistical significance ($p<0.001$) throughout the whole year in the future period (2071–2100) as compared to the reference period (2006–2014) (Figures 1–6; Table 1). The largest future concentrations of indicators were found for the three indicator bacteria *E. coli*, coliforms and intestinal enterococci in the western part of Norway (Figure 1; Table 1). The largest percentage increases in indicator concentrations were found in the western and northern regions, for all indicators (Figures 2–6). The 99th percentile of *E. coli* concentration is estimated to increase by 410% in the north (corresponding to a five-fold increase, from 1 colony-forming unit (CFU)/100 mL raw water to 5.1 CFU/100 mL), throughout the whole year. In the West, its concentration is estimated to double. The largest increase throughout the whole year (in percentages) is found for the 99th percentile of intestinal enterococci bacteria concentration in the North with an estimated future increase of 467% (from 0.3 to 1.7 CFU/100 mL) (Table 1). Seasonally, the largest increases in indicator levels were found in summer and autumn in the western and northern parts of Norway.

Using the effect from future changes in runoff, the results varied, with some indicators increasing and others decreasing (Figures 1–6; Table 1). Throughout the whole year, we found only very small changes in most of the water quality indicators and regions due to changes in runoff (mostly <2%). When stratifying by season, the estimated changes were also small and there were few results with statistical significance. We registered, however, a small, but statistically significant increase in all

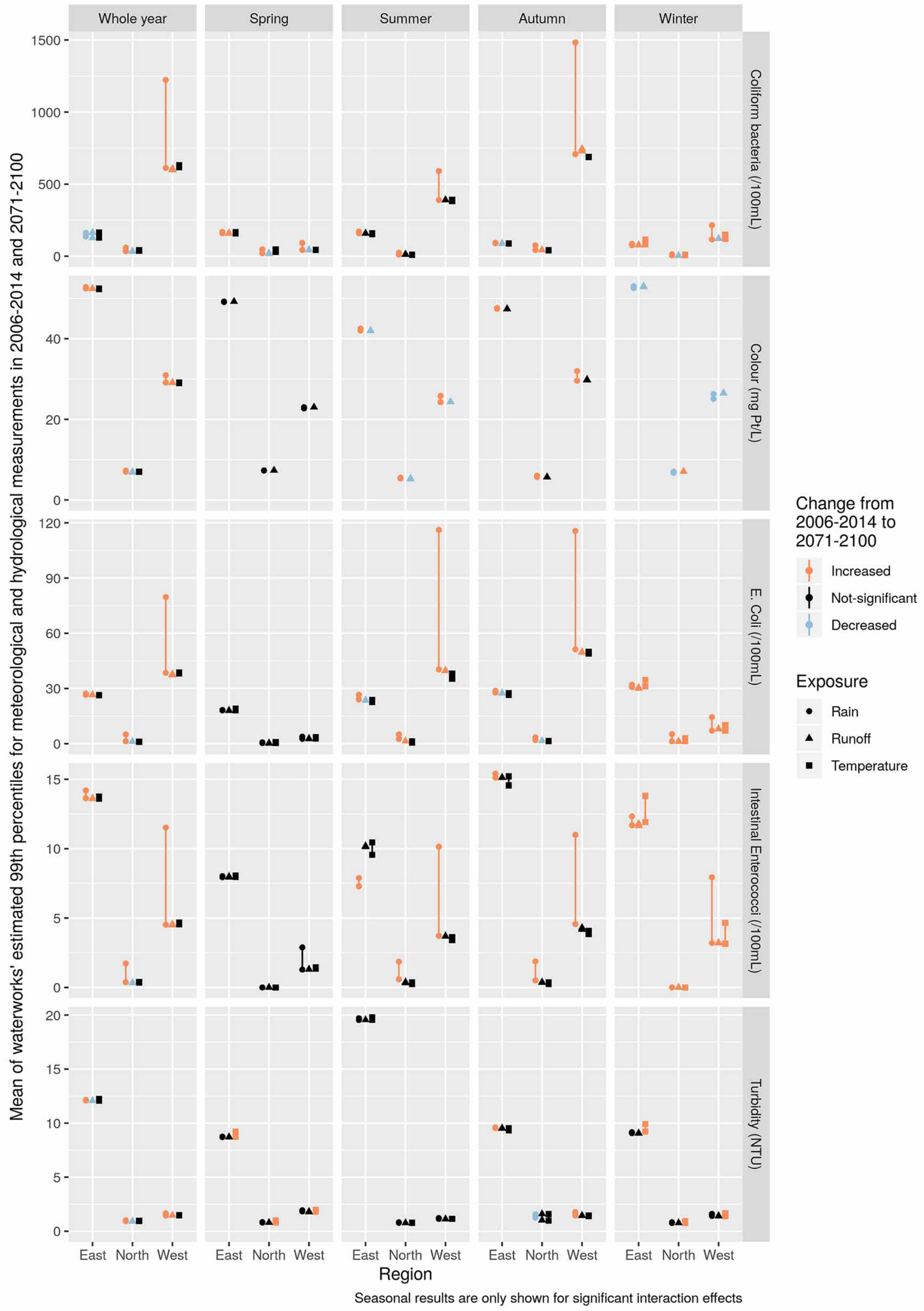

Figure 1 | The means of the waterworks' estimated 99th percentile of water quality indicators for raw water in the different regions, shown for the base period (2006–2014) and the future period (2071–2100) under the high scenario (RCP8.5). Each of the dots represents the means of the 99th percentile. The line indicates that the two points are related to each other and refers to the expected magnitude of change over time.

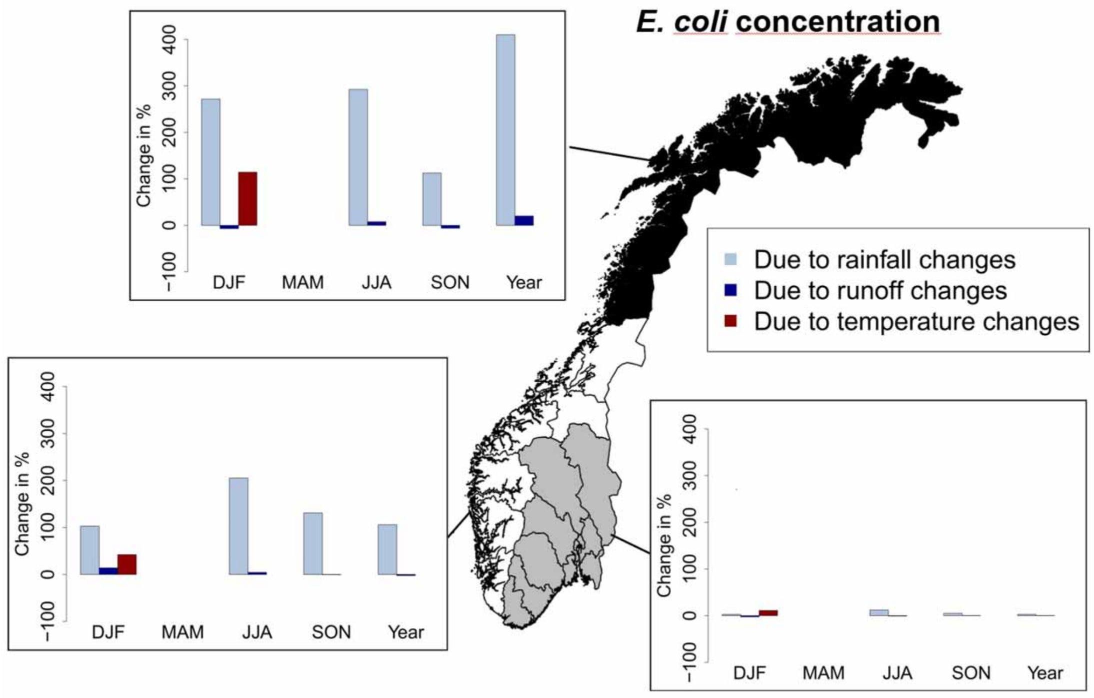

Figure 2 | Percentage change in the 99th percentile of *E. coli* concentration in raw water from 2006–2014 to 2071–2100 under the high scenario (RCP 8.5), for the various seasons (DJF=winter (December–February), MAM=spring (March–May), JJA=summer (July–August) and SON=autumn (September–November)) and for the regions North, West and East. Only statistically significant changes are included. See Table 1 for the values in original units.

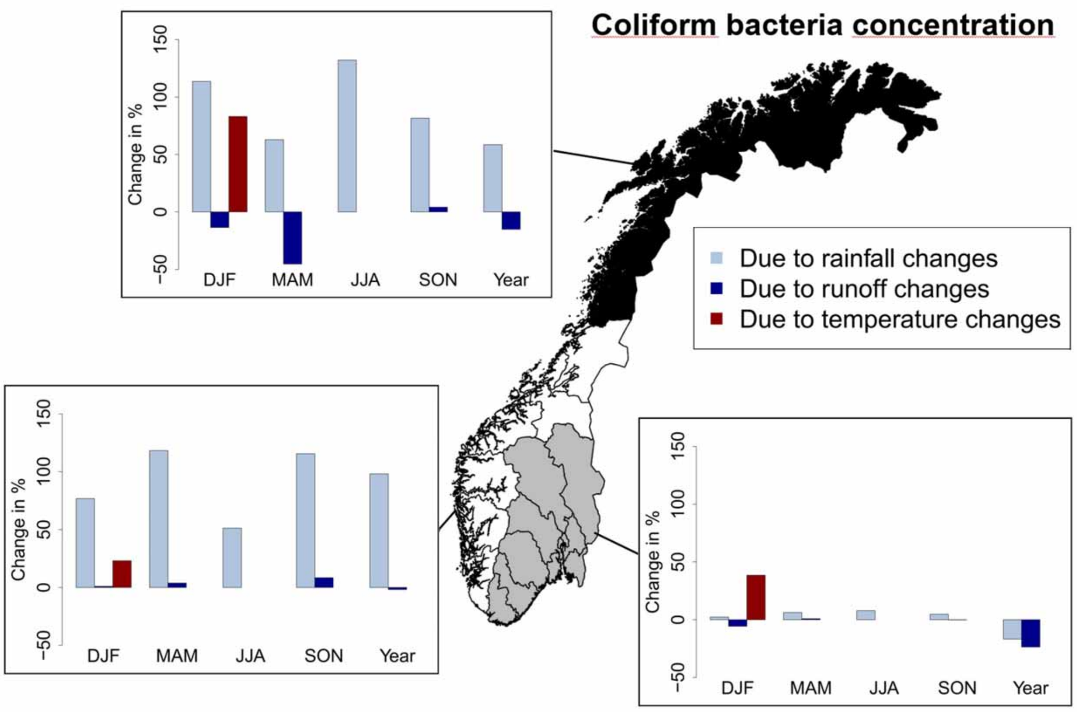

Figure 3 | Percentage change in the 99th percentile of coliform bacteria concentration in raw water from 2006–2014 to 2071–2100 under the high scenario (RCP 8.5), for the various seasons (DJF=winter (December–February), MAM=spring (March–May), JJA=summer (July–August) and SON=autumn (September–November)) and for the regions North, West and East. Only statistically significant changes are included. See Table 1 for the values in original units.

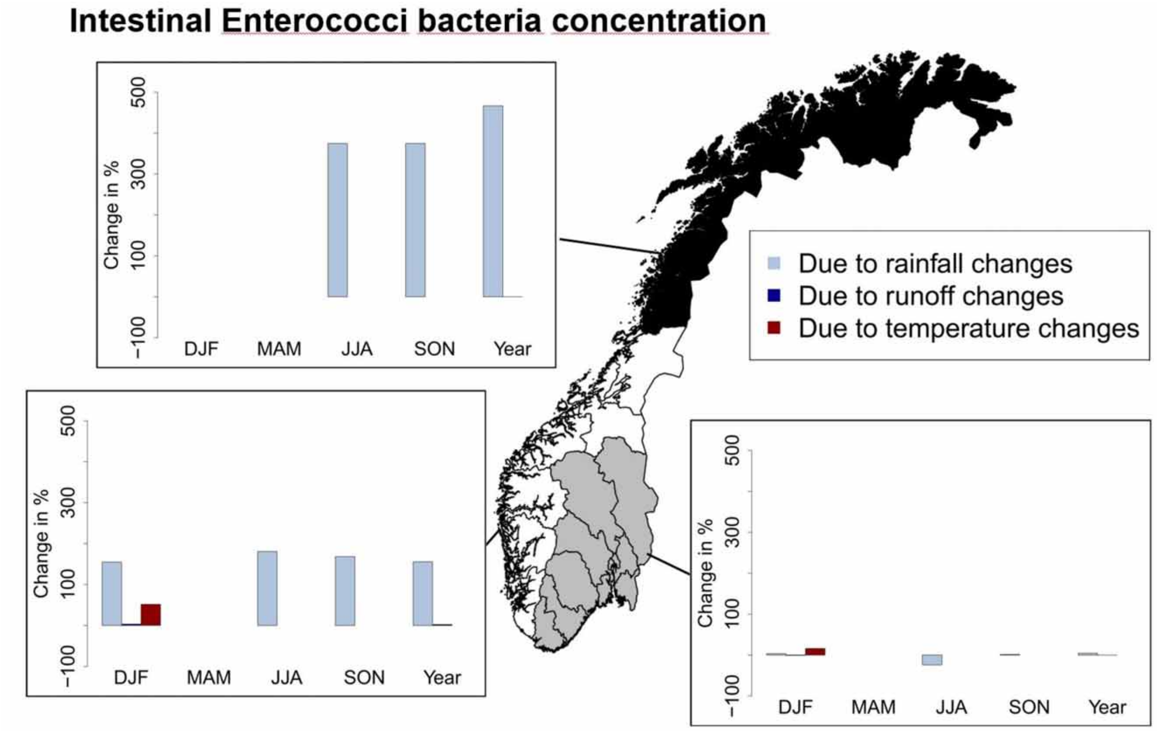

Figure 4 | Percentage change in the 99th percentile of intestinal enterococci bacteria concentration in raw water from 2006–2014 to 2071–2100 under the high scenario (RCP 8.5), for the various seasons (DJF=winter (December–February), MAM=spring (March–May), JJA=summer (July–August) and SON=autumn (September–November)) and for the regions North, West and East. Only statistically significant changes are included. See Table 1 for the values in original units.

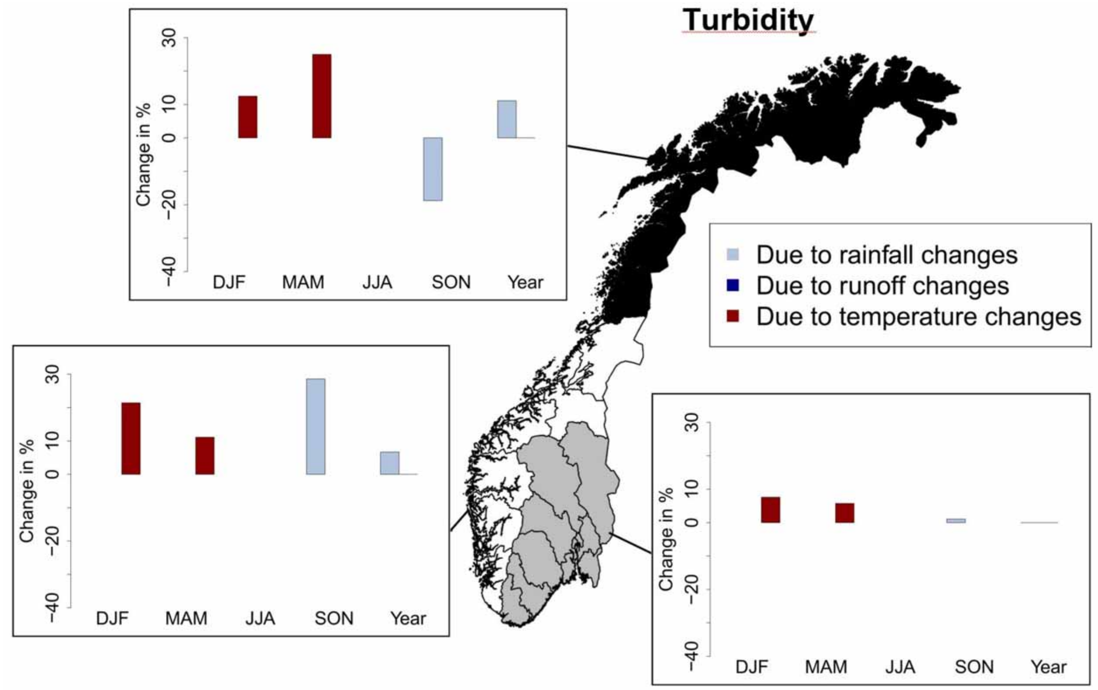

Figure 5 | Percentage change in the 99th percentile of turbidity in raw water from 2006–2014 to 2071–2100 under the high scenario (RCP 8.5), for the various seasons (DJF=winter (December–February), MAM=spring (March–May), JJA=summer (July–August) and SON=autumn (September–November)) and for the regions North, West and East. Only statistically significant changes are included. See Table 1 for the values in original units.

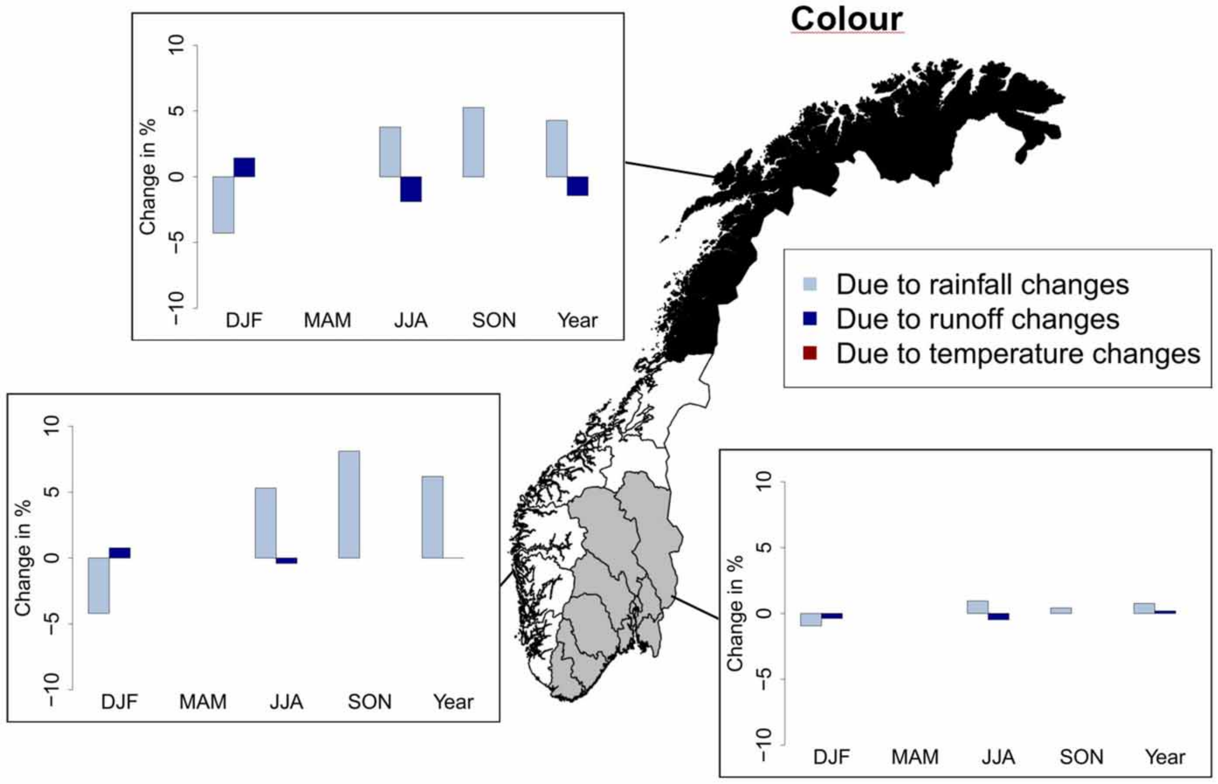

Figure 6 | Percentage change in the 99th percentile of colour in raw water from 2006–2014 to 2071–2100 under the high scenario (RCP 8.5), for the various seasons (DJF=winter (December–February), MAM=spring (March–May), JJA=summer (July–August) and SON=autumn (September–November)) and for the regions North, West and East. Only statistically significant changes are included. See Table 1 for the values in original units.

indicator bacteria concentrations as well as colour in the winter season in the West and a decrease in the colour in summer in all regions.

With future changes in maximum temperature, we found no changes in the water quality indicators that were statistically significant when the whole year was considered (Table 1). However, for the winter season, we estimated clear effects from the increasing maximum temperature. We found an increase in all regions for *E. coli*, coliform bacteria, turbidity and for intestinal enterococci in the East and the West (no concentration was measured in the North). The largest estimated increase is estimated for the *E. coli* concentration in the north, by 114.3% (from 1.4 to 3.0 CFU/100 mL). We also found an increase in turbidity in winter and spring in all regions, as a result of the increased maximum temperature.

DISCUSSION

We found increasing future levels of raw water quality indicators throughout the whole year by the end of the century due to future changes in rainfall, with the largest effects in the North and the West. In the East, small changes were seen. This follows from the finding that increased rain was associated with increased levels of coliform bacteria, *E. coli*, intestinal enterococci, colour and turbidity in Norway throughout the whole year (Guzman Herrador *et al.* 2021). Furthermore, the annual precipitation in Norway is projected to increase by about 18% from 1971–2000 to 2071–2100 (Hanssen-Bauer *et al.* 2015), with the largest increases estimated for the northern and western regions of the country.

Seasonally, the results due to future changes in rainfall vary more and depend on both regions, seasons and water quality indicators. While the variations between the indicators can be understood from the differences in the associations found by Guzman Herrador *et al.* (2021), the seasonal and regional variability may be explained by climatological differences. In the North and the West, most of the indicators show a substantial increase in their future concentrations during the summer and autumn seasons. These are the seasons when the future precipitation is projected to increase the most in the North and West by the end of the century (Hanssen-Bauer *et al.* 2015).

Table 1 | Historical and future concentrations of water quality indicators coliform bacteria, colour, *E. coli*, intestinal enterococci and turbidity in raw water in the three geographical regions, for each season and the whole year

Region	Indicator	Unit	Season	p99 base period	Rainfall p99 future	Runoff p99 future	Temperature p99 future
East	Coliform	/100 mL	Whole year	164.7	137.1*	125.8*	129.8
East	Coliform	/100 mL	Spring	158.8	168.8*	160.2*	168.6
East	Coliform	/100 mL	Summer	158.5	170.9*	159.1	153.0
East	Coliform	/100 mL	Autumn	88.3	92.5*	88.2*	88.5
East	Coliform	/100 mL	Winter	82.9	84.8*	78.2*	114.8*
East	Colour	mg Pt/L	Whole year	52.4	52.8*	52.5*	52.2
East	Colour	mg Pt/L	Spring	49.2	49.1	49.2	–
East	Colour	mg Pt/L	Summer	42.1	42.5*	41.9*	–
East	Colour	mg Pt/L	Autumn	47.4	47.6*	47.4	–
East	Colour	mg Pt/L	Winter	53.0	52.5*	52.8*	–
East	*E. coli*	/100 mL	Whole year	26.5	27.2*	26.6*	26.3
East	*E. coli*	/100 mL	Spring	18.2	18.3	18.1	19.1
East	*E. coli*	/100 mL	Summer	23.7	26.6*	23.5*	22.6
East	*E. coli*	/100 mL	Autumn	27.4	28.8*	27.5*	26.6
East	*E. coli*	/100 mL	Winter	31.2	32.0*	30.4*	34.7*
East	Int. enterococci	/100 mL	Whole year	13.6	14.2*	13.6*	13.7
East	Int. enterococci	/100 mL	Spring	8.0	8.0	8.0	8.1
East	Int. enterococci	/100 mL	Summer	10.4	7.9*	10.1	9.6
East	Int. enterococci	/100 mL	Autumn	15.2	15.4*	15.1	14.6
East	Int. enterococci	/100 mL	Winter	11.9	12.3*	11.8*	13.8*
East	Turbidity	NTU	Whole year	12.1	12.1*	12.1*	12.2
East	Turbidity	NTU	Spring	8.7	8.8	8.7	9.2*
East	Turbidity	NTU	Summer	19.5	19.7	19.5	19.8
East	Turbidity	NTU	Autumn	9.5	9.6*	9.5	9.3
East	Turbidity	NTU	Winter	9.2	9.2	9.1	9.9*
North	Coliform	/100 mL	Whole year	37.6	59.6*	31.9*	41.1
North	Coliform	/100 mL	Spring	29.1	47.4*	15.9*	46.0
North	Coliform	/100 mL	Summer	10.3	23.9*	13.8	8.7
North	Coliform	/100 mL	Autumn	41.3	75.0*	43.0*	41.5
North	Coliform	/100 mL	Winter	5.9	12.6*	5.1*	10.8*
North	Colour	mg Pt/L	Whole year	7.0	7.3*	6.9*	7.0
North	Colour	mg Pt/L	Spring	7.3	7.3	7.3	–
North	Colour	mg Pt/L	Summer	5.3	5.5*	5.2*	–
North	Colour	mg Pt/L	Autumn	5.7	6.0*	5.7	–
North	Colour	mg Pt/L	Winter	7.0	6.7*	7.1*	–
North	*E. Coli*	/100 mL	Whole year	1.0	5.1*	1.2*	0.9
North	*E. Coli*	/100 mL	Spring	0.4	0.8	0.3	0.9
North	*E. Coli*	/100 mL	Summer	1.3	5.1*	1.4*	0.5
North	*E. Coli*	/100 mL	Autumn	1.6	3.4*	1.5*	1.3
North	*E. Coli*	/100 mL	Winter	1.4	5.2*	1.3*	3.0*
North	Int. enterococci	/100 mL	Whole year	0.3	1.7*	0.3*	0.4

(*Continued.*)

Table 1 | Continued

Region	Indicator	Unit	Season	p99 base period	Rainfall p99 future	Runoff p99 future	Temperature p99 future
North	Int. enterococci	/100 mL	Spring	0.0	0.0	0.0	0.0
North	Int. enterococci	/100 mL	Summer	0.4	1.9*	0.3	0.3
North	Int. enterococci	/100 mL	Autumn	0.4	1.9*	0.4	0.3
North	Int. enterococci	/100 mL	Winter	0.0	0.0*	0.0*	0.0*
North	Turbidity	NTU	Whole year	0.9	1.0*	0.9*	1.0
North	Turbidity	NTU	Spring	0.8	0.9	0.8	1.0*
North	Turbidity	NTU	Summer	0.8	0.8	0.8	0.8
North	Turbidity	NTU	Autumn	1.6	1.3*	1.0	1.0
North	Turbidity	NTU	Winter	0.8	0.8	0.8	0.9*
West	Coliform	/100 mL	Whole year	617.3	1,223.1*	606.3*	633.0
West	Coliform	/100 mL	Spring	42.1	91.9*	43.7*	45.1
West	Coliform	/100 mL	Summer	390.5	590.5*	390.8	381.1
West	Coliform	/100 mL	Autumn	688.0	1,483.5*	746.0*	689.6
West	Coliform	/100 mL	Winter	121.2	214.3*	122.4*	149.2*
West	Colour	mg Pt/L	Whole year	29.1	30.9*	29.1*	29.0
West	Colour	mg Pt/L	Spring	23.0	22.7	23.0	–
West	Colour	mg Pt/L	Summer	24.5	25.8*	24.4*	–
West	Colour	mg Pt/L	Autumn	29.6	32.0*	29.9	–
West	Colour	mg Pt/L	Winter	26.2	25.1*	26.4*	–
West	*E. Coli*	/100 mL	Whole year	38.7	79.7*	37.8*	38.2
West	*E. Coli*	/100 mL	Spring	2.7	3.8	2.7	3.6
West	*E. Coli*	/100 mL	Summer	38.1	116.2*	39.8*	35.4
West	*E. Coli*	/100 mL	Autumn	50.0	115.5*	49.8*	49.0
West	*E. Coli*	/100 mL	Winter	7.1	14.4*	8.1*	10.1*
West	Int. enterococci	/100 mL	Whole year	4.5	11.5*	4.6*	4.7
West	Int. enterococci	/100 mL	Spring	1.3	2.9	1.3	1.4
West	Int. enterococci	/100 mL	Summer	3.6	10.1*	3.7	3.4
West	Int. enterococci	/100 mL	Autumn	4.1	11.0*	4.3	3.8
West	Int. enterococci	/100 mL	Winter	3.1	7.9*	3.2*	4.7*
West	Turbidity	NTU	Whole year	1.5	1.6*	1.5*	1.5
West	Turbidity	NTU	Spring	1.8	1.9	1.8	2.0*
West	Turbidity	NTU	Summer	1.1	1.2	1.1	1.2
West	Turbidity	NTU	Autumn	1.4	1.8*	1.4	1.4
West	Turbidity	NTU	Winter	1.4	1.6	1.4	1.7*

The 99th percentile (p99) of the quality indicators are shown for both the base period (2006–2014) and for the future period (2071–2100) under the high scenario (RCP 8.5) when considering the effect from changes in weekly mean rainfall, runoff and maximum temperature. Numbers marked with a '*' have a statistically significant difference between 2006–2014 and 2071–2100. Cells that contain only '–' are seasonal models that have non-significant seasonal interaction terms.

The fact that we estimate small changes in raw water quality when taking into account the effect from future changes in runoff may be explained by the future projections of runoff. Here, the results are inconsistent from model to model. On average for the whole country, the median of 10 models gives an increase of 7% in annual runoff for Norway from 1971–2000 to 2071–2100, but due to the disagreement between models, the estimate spans from −3 to +11% change (Hanssen-Bauer *et al.* 2015). The runoff is also generally estimated to decrease along the coast and in lower-lying areas, and to increase in mountains and inner parts of Nordland and Finnmark, which makes it difficult to capture consistent regional signals in the estimates.

The projected runoff is estimated to change much more consistently with season than annually, especially in winter and summer (Hanssen-Bauer *et al.* 2015). In winter, the runoff is estimated to increase, whereas in summer, it is estimated to decrease. This is shown in all regions. This supports the estimated future increase in all indicator concentrations as well as colour in the winter season in the West, and the decrease in the colour in summer in all regions, when the effect from changing runoff is included. A model study of a Norwegian catchment indicates lower future concentrations of *E. coli* in summer due to reduced runoff (Mohammed *et al.* 2019).

Several studies support the link between future changes in rainfall and runoff and decreasing drinking water quality (Delpla *et al.* 2009; Leveque *et al.* 2021). In the USA, half the waterborne disease outbreaks during the last half-century followed a period of extreme rainfall (Curriero *et al.* 2001). Seasonal and interannual variability in local rainfall are found to explain nearly 70% of the variability in the coliform records in the UK (Pednekar *et al.* 2005).

With future changes in the maximum temperature, small changes are seen in the water quality indicators when the whole year is considered (Figures 1–6; Table 1). The annual mean temperature for Norway is estimated to increase by about 4.5 °C from 1971–2000 to 2071–2100 (Hanssen-Bauer *et al.* 2015); however, no significant associations were found between temperature and water quality indicators throughout the whole year. Statistically significant changes due to changing temperature were mainly found in winter, and in winter and spring for turbidity. The reason for this may be that warmer winters with shorter periods of ice cover on lakes may reduce the hygienic barrier efficiency against pathogen transport from the surface to the deep-water intake in deep lakes used as drinking water sources (Tryland *et al.* 2011; Guzman Herrador *et al.* 2021). The main water sources in Norway are lakes, covered with ice during winter. The ice cover is normally a natural protection against microbes and particles flushing into the water source and prevents an increase in both microbial content and turbidity. However, in recent years, the period of ice cover has decreased. The winters are now milder and are more often associated with air temperatures above 0 °C. Observations of daily maximum temperature show the largest increase in winter. In the future, the largest increase in temperature is also projected for the winter season (Hanssen-Bauer *et al.* 2015).

In order to get a good estimate of the climate and hydrology at a location, a series with at least 30 years of data should be used. In this study, the water quality data from the waterworks only covered the period from 2006 to 2014. We also have a relatively limited number of waterworks included in our study, with especially few waterworks located in the northern part of Norway. Therefore, we divided the country into only three simplified geographical climate regions. Norway is a country with large variations in temperature and precipitation depending on the region and height above sea level (Førland *et al.* 2000). As a result, we may not have captured the entire climate and hydrological variability that the waterwork locations represent.

Our analyses were based on associations between weekly averages of raw water quality and meteorological and hydrological variables (Guzman Herrador *et al.* 2021). Water quality data for raw water were received as weekly averages from the waterworks. A quantitative analysis of changes in extreme precipitation or floods over a shorter time resolution was thus not made. Perhaps this may explain the small effects on water quality found in the Eastern part of the country, where short-duration extreme precipitation is more common than in the North and West. Several studies demonstrate impacts of short-term rainfall events on water quality (Roig *et al.* 2011; Zhu *et al.* 2021). A follow-up study using higher time resolutions of both water quality and meteorological and hydrological data would allow further investigations of the effects from changes in short-duration extreme rainfall and subsequent runoff events on drinking water quality.

When it comes to the future climate projections, emission scenarios, climate models and the downscaling procedures include several uncertainties (Hanssen-Bauer *et al.* 2015; Wong *et al.* 2016). Uncertainties in climate models are reduced by using several (here 10) models for the analyses. It should, however, be noted that the results get more uncertain with higher resolution in time and space. That means that seasonal estimates are more uncertain than annual estimates, and regional/local estimates are more uncertain than national estimates.

With climate change, other factors may also possibly affect the raw water quality. For instance, land-use change and longer growing seasons could increase the use of fertilisers with subsequent leaching to watercourses, rivers and lakes, causing higher levels of contaminants in the water (Arheimer *et al.* 2005; Whitehead *et al.* 2009). Small lakes with short residence times will also be more sensitive to changes in rainfall and runoff than large ones (George *et al.* 2007).

Increased levels of water quality indicators in raw water may lead to public health issues if the waterworks do not have treatment processes that are capable of cleaning the water properly before distributing it to the public (Khan *et al.* 2015). Few associations between weather/hydrology and water quality indicators were found in treated water (Guzman Herrador *et al.* 2021), meaning that the waterworks included were able to cope with the present levels of quality indicators. However, only large waterworks were included. Smaller waterworks may not have the resources and capacities needed for treating the raw water sufficiently. In addition, private supplies would be at risk (Hunter 2003).

CONCLUSIONS

The results of our study suggest that with continued climate change, the raw water quality will deteriorate by the end of the century. The degradation of water quality follows from estimated higher levels of water quality indicators in the future, especially due to increasing amounts of rainfall. Regionally, the largest effects were seen in the Western and Northern parts of Norway, with very small changes found in the East. The concentrations of bacteria, turbidity and colour predicted in raw water for the end of this century are, however, relatively small. Thus, it is likely that the large waterworks will adapt to future conditions. Any designs for new treatment systems will have to include effects from climate change, and new operational procedures may be required in the future. Furthermore, the estimated deterioration of raw water quality may cause future challenges for the treatment processes at smaller waterworks and for private supplies.

Our results may be used for assessing the need for an upgrade in treatment capacity at the waterworks in association with climate change. Combining the results with further studies of treatment effects and microbial risk assessments is needed in order to ensure sufficient treatment capacities of the raw water in the future. Whereas this study includes effects from changing climate on the raw water of the waterworks, well-functioning water distribution systems are also necessary in order to ensure the distribution of high-quality drinking water from the waterworks to the public.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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