Understanding changes and trends in projected hydroclimatic indices in selected Norwegian and Polish catchments

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Received: 17 February 2017 / Accepted: 10 July 2017 / Published online: 28 August 2017
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Abstract The aim of the study is to investigate trends in selected hydroclimatic indices using novel and conventional tools, for future climate projections in the twenty-first century. Selected quasi-natural Norwegian and Polish catchments are used as a case study. The projected flows are provided by GR4J rainfall-runoff conceptual model, coupled with an ensemble of climate model projections from EURO-CORDEX initiative. The trends are analysed using conventional Mann–Kendall and modified Mann–Kendall statistical approaches, a time–frequency approach based on discrete wavelet transform (DWT) and the dynamic harmonic regression (DHR) method. Of all methods applied the DHR gives the most conservative trend estimates. Trends depend on the specific hydroclimatic character and flow regime of the catchment. The results confirmed that in catchments with a rainfall-driven flood regime, an increase in the amount of precipitation is followed by increased flows, with strong seasonal changes, whereas, in catchments with a snow-driven flood regime, despite an increase of mean annual flow, decrease in annual maximum flow is observed. Generally, positive trend is the most dominant in all catchments studied and the methods

were consistent in detection of trend except in seasonal trend test.

Keywords Hydroclimatic indices · Trends · Climate change · GR4J · Poland · Norway

Introduction

In the long term, global warming leads to changes in climate variables and can have a serious impact on hydrological extremes, water resources, agriculture systems, environmental ecology and human lives. Joint natural and anthropogenic activities are the main causes of the changes in climate extreme events and the consequent changes in hydrological extremes (IPCC 2013).

The global climate is warming, and the tendency of precipitation and air temperature rising at the earth's surface is strengthening. The increase in global precipitation and temperature favours the intensity and frequency increase of climatic phenomena (IPCC, 2011). RCMs/GCMs simulations over Europe have revealed that the temperature and precipitation show a warming band of mean annual temperatures which extends from south-western to north-eastern Europe (Fleig et al. 2015). Whilst precipitation pattern shows increasing trends for parts of North Europe, no trends for Central and Eastern Europe and a clear negative trend for South Europe (Fleig et al. 2015) are visible. Future climate scenarios generally suggest an increase of precipitation and air temperature in the twenty-first century in Poland and Norway (Madsen et al. 2014; Osuch et al. 2016). However, there are differences in estimated trends of future flow projections in Europe (Papadimitriou et al. 2016; Vautard et al. 2016) and in different parts of the world (Wilson et al. 2010; Rojas et al.

Electronic supplementary material The online version of this article (doi:10.1007/s11600-017-0062-5) contains supplementary material, which is available to authorized users.

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2012; Alfieri et al. 2016; Meresa and Gatachew 2016; Kundzewicz et al. 2017). The main reasons for those diverse outcomes can be attributed to differences in temporal and spatial scale of rainfall-runoff models applied to transform precipitation into flow, regional and climatic differences, differences in climate projections used as inputs and trend assessment uncertainty.

The detection of trends of hydrological and climatic indices, in particular indices derived from precipitation, temperature and streamflow, is essential for an assessment of the impacts of climate change and variability and hydrological change on both regional and catchment scales (Wilson et al. 2010; Stahl et al. 2010; Łupikasza et al. 2011; Madsen et al. 2014). The main focus of these and many other studies was to identify trends for the purpose of water resource availability assessment, future risk reduction and adaptation, water resource planning and management and seasonal variability and seasonal interconnection, which is a vital issue in hydrology and meteorology.

To deal with uncertainty in trend detection, many authors have employed both parametric and nonparametric statistical tests. Shao et al. (2010) pointed out that most of the methods used in the literature are unable to detect both long-term trends and abrupt changes simultaneously. Common nonparametric approaches, such as the Mann–Kendall (MK), the Wilcoxon–Mann–Whitney, t test and Pettit’s test, can only detect a monotonic trend or a single abrupt change (Shao et al. 2010). In this study we decided to apply the MK test due to its popularity in the environmental studies. The use of any one of these tests alone cannot efficiently detect trends in hydrological time series. This is because hydrological time series are known to often exhibit multiple abrupt changes and varying trends occurring in different periods, which are caused by interannual and decadal variability associated with the climate system (Peel and McMahon 2006). Additionally, classical trend tests do not deal well with the effects of persistence and seasonality (Cluis et al. 1989). Some authors have also attempted to detect the trend and abrupt changes in time series separately (e.g. Zhao et al. 2008), but this approach is not statistically satisfactory because the conclusions obtained from different tests may not be compatible (Shao et al. 2010). Though a single trend test is considered appropriate for trend testing and detection with specified start and end times, it does not show whether any changes are due to gradual or abrupt occurrences (Zhang et al. 2010). Mohsin and Gough (2010) recognized that a number of trend-related studies contained some flaws because when using trend detection tests, such as the Mann–Kendall test, the studies did not include testing for autocorrelation. They simply assumed that the observations contained in the time series being analysed were serially independent. The effect of one data point on the next one (serial correlation) in a

sequential times series can lead to a misleading interpretation (Yue et al. 2002). The rejection of the null hypothesis (understood here as “no trend”) will be more likely to occur when in fact it should be accepted (Hamed and Rao 1998; Partal 2010). Positive serial correlation can lead to an increase in falsely rejecting the null hypothesis (Douglas et al. 2000), whereas the presence of a negative serial correlation can lead to an increase in falsely accepting the null hypothesis (Yue and Wang 2004). As such, it is important to address the issue of serial correlation in time series prior to applying a trend test. Then if the time series are free of serial correlation and seasonality, the MK test can be used, whilst when a significant correlation in the time series exists, extended versions of the original MK test should be applied.

The MK-based statistical approaches assume stationary time series. The dynamic harmonic regression (DHR) and discrete wavelet transform (DWT) methods are robust in capturing nonstationary, oscillatory and abrupt change behaviour. Unlike the conventional MK-based methods, they allow the low-frequency variation (trend) and other seasonal/cyclic frequency components to be estimated. To our knowledge, these methods have not yet been applied in the analysis of trends of future climatic and hydrological projections.

This paper aims to: (1) simulate catchment flows by coupling GR4J hydrological model and climate models, (2) compare the results of trend analysis using four different techniques for different hydroclimatic conditions of Polish and Norwegian catchments; (3) determine whether there is evidence of a statistically significant trend of different indices derived from hydroclimatic projections; (4) compare the changes in hydroclimate indices in near (2021–2050) and far (2071–2100) future with long-term 130-year window trend estimates.

The structure of the paper is as follows. “Study areas and hydroclimatic data” describes the geographical location of selected gauging stations and their hydroclimatic characteristics. In “Methodology” the data used in this study are presented including both observations and future projections. The methods used for trend detection are presented in “Results”. The trends found for each indices derived from streamflow, temperature and precipitation time series are discussed in “Discussion”. Finally, the conclusions of our study are presented in “Conclusions”.

Study areas and hydroclimatic data

Study area and observed data characteristics

The selection of Polish and Norwegian catchments included in this study was described by Romanowicz et al.

Table 1 List of selected Polish and Norwegian catchments

Code	Catchment	Gauged @	Area (km ²)	Flood regime	Pm ^b	Qm ^a
C1	Dunajec	Nowy Targ Kowaniec	681.1	Rainfall	3.1	14.5
C2	Wisła	Skoczów	296.5	Mixed	2.6	6.1
C3	Biała Tarnowska	Koszyce wielkie	966.9	Mixed	2.1	9
C4	Nysa Kłodzka	Kłodzko	1061.5	Mixed	2.1	12.9
C5	Oleśnica	Niechmirow	583.5	Snow melt	1.6	2.5
C6	Łasica	Władysławów	629.29	Snow melt	1.5	1.1
C7	Narewka	Narewka	635.3	Snow melt	1.8	3
C8	Flinta	Ryczywół	271.44	Snow melt	1.5	0.7
C9	Myśla	Myslibórz	586.88	Snow melt	1.5	1.3
C10	Guber	Prosna	1554.5	Snow melt	1.6	8.5
CC1	Ardal	Moisani/Sira	77.25	Rain	9.28	12.54
CC2	Eggedal	Simoa/Drammen	309.77	Mixed	3.8	6.87
CC3	Fustvatn	Fusta	525.69	Mixed	6.55	32.67
CC4	Krinsvatn	Bordelva	206.61	Rain	6.75	12.64
CC5	Myglevatn	Kosana/Mandalselva	182.2	Rain	6.13	7.96
CC6	Polmak	Tana	14161.4	Snow melt	1.4	179.23
CC7	Viksvatn	Gaular	508.13	Rain	10.45	44.82
CC8	Atnasjø	Atna/Glomma	463.2	Snow melt	2.33	10.19

^a Qm [m³/s] is an average value of streamflow daily

^b Pm [mm] is an average value of precipitation daily

(2016). Nearly natural catchments were selected to minimize the impact of human activity on catchment runoff. As a result of careful analysis, eight Norwegian and ten Polish catchments were selected. Table 1 provides details of the catchment descriptors and lists gauging stations corresponding to each catchment. The catchments have a diversified hydroclimatic conditions. The watershed area ranges from 77.25 (Ardal-Norwegian catchment) to 1554.5 km² (Guber-Polish catchment). They are covered mostly by forest and do not have any reservoirs. The flood regime is driven by rainfall and/or snow melt (Table 1). Among Polish catchments, only Dunajec has rainfall-driven flood regime, Biała Tarnowska and Nysa Kłodzka have mixed flood regime, and the rest of the catchments have snow-melt-driven flood regime. The Norwegian catchments have mainly rain-driven flood regimes, with only two catchments having snow-driven flood regime and two other with mixed flood regime.

The location of Polish catchments is given in Fig. 1. Also shown are dominating flood regimes in the catchments, including snow-melt, rainfall and mixed flood regime. The selected catchments are located in varying hydroclimatic conditions: Nysa Kłodzka, Wisła, Dunajec and Biała Tarnowska are in the highlands (southern Poland); Myśla and Flinta are in the eastern part of Poland; Łasica and Oleśnica are in the central part; Narewka and Guber are located in the north-east part of the country.

The location of the Norwegian catchments is shown in Fig. 2. Following the description given by Romanowicz

et al. (2016), Polmak and Atnasjø catchments have snow-melt-driven flood regimes. The Krinsvatn and Ardal have rainfall-driven flood regimes, and the rest of the catchments have mixed flood regime. As in the case of the Polish catchments, the Norwegian catchments are characterized by nearly natural land-use conditions.

Observed hydrological and climate data

The available observations include daily temperature, precipitation and flow time series for the period 1971–2009. As described by Romanowicz et al. (2016), the annual sums of precipitation and annual mean temperature observed values in the selected ten catchments in Poland and eight catchments in Norway for so-called reference period (1971–2000) shows a slight increase of temperature after 1985 in all catchments. Precipitation time series in all catchments do not show clear trends. The lowest precipitation and temperature values were for 1982 and 1980, respectively. Spatially, the lowest precipitation and temperature values are found in the north-west, middle and north-east parts of Poland (Myśla, Flinta), Oleśnica and Guber.

Long-term observed discharge data are also needed for hydrological model validation and calibration. The observed discharge data at all the selected catchments (Figs. 1, 2) were obtained from the Institute of Meteorology and Water Management in Poland and from the Met-Office in Norway, respectively.

Fig. 1 Location of selected catchments in Poland

Projected climate time series data: precipitation and temperature

Climate change data used in the present study originate from the EURO-CORDEX initiative (<http://www.eurocordex.net>). Assessments of the EURO-CORDEX projections have shown that they are capable to accurately reproduce regional-scale climate variability, especially when using the 0.11 degree resolution (Kotlarski et al. 2014; Truhetz et al. 2014). Seven climate model projections resulting from combinations of three GCMs and five RCMs under RCP 4.5 emission scenario (Moss et al. 2010; Jacob et al. 2014) were used. The EUR-11 RCP 4.5 output

has a spatial resolution of 0.11×0.11 degrees or approximately 12.5 km. This exceptionally fine spatial resolution allows for more accurate modelling of orographic effects, among other benefits. The RCP 4.5 was applied because it is a stabilization scenario and thus assumes the imposition of emissions mitigation policies. Also, the RCP 4.5 is derived from its own “reference”, or “no-climate-policy”, scenario.

The daily GCM/RCM output provided input to the hydrological models. The full description of the projected climate time series is given by Meresa et al. (2016). Table 2 shows details of the applied GCM/RCMs.

Fig. 2 Location of selected catchments in Norway

Table 2 List of the GCM/RCMs applied

GCM	RCM	Institute
EC-EARTH	RCA4	Swedish Meteorological and Hydrological Institute
EC-EARTH	HIRHAM5	Danish Meteorological Institute
EC-EARTH	CCLM-4-8-17	NCAR UCAR
EC-EARTH	RACMO22E	Meteorological institute
MPI-ESM-LR	CCLM4-8-17	Max Planck Institute for Meteorology
MPI-ESM-LR	RCA4	Max Planck Institute for Meteorology
CNRM-CM5	CCLM4-8-17	CERFACS, France

Streamflow and precipitation extreme indices

The choice of indices derived from hydrological and meteorological variables depends mainly on the objectives

of the research. There are different indices for agricultural production, drainage of urban and agricultural lands, erosion, flood, drought and water resources management and planning (Morán-Tejeda et al. 2011; Ijaz et al. 2015; Sonali

Table 3 Indices selected for the study

Index	Extended name	Units
AMaxQ/AMeanQ	Annual maximum/mean flow	m ³ /s
MAXQ1/MAXQ2/	DJF/JJA seasonal maximum flow	m ³ /s
ASumP/AMaxP	Annual sum/maximum precipitation	mm
SSP1/SSP2	DJF/JJA sum seasonal precipitation	mm
AMeanT	Annual mean temperature	°C

and Kumar 2013; Hu et al. 2007; Santos and da Silva 2015). The indices chosen for this study are listed in Table 3. They were calculated from daily data sets for projected flow, temperature and precipitation for the period 1971–2100. The choice was dictated by the major goal of the study, which is understanding the estimates of changes in hydrological future projections. Apart from annual maximum, seasonal maximum flow indices were also chosen in order to see any possible changes in seasonal patterns of extreme flows. Annual and seasonal sums of precipitation and annual mean temperature indices were chosen to provide the meteorological background of future climate projections. The seasonal analysis presented here is limited to the winter season (December–January–February DJF) and the summer season (June–July–August JJA) for the sake of clarity of the discussion. These two seasons showed the largest changes in future projections. The climate projections were bias corrected. We used the same technique of climate bias correction as used by Romanowicz et al. (2016) and Meresa et al. (2016). Single gamma quantile distribution mapping with wet day number correction was used for the precipitation, and empirical quantile mapping was used for the temperature records. The future flow simulations were driven by corrected precipitation and temperature.

Methodology

The general framework of our research approach is presented in Fig. 3. It consists of four main stages. They include the calibration and validation of hydrological models for each catchment studied using the available observations, bias correction of future projections of climatic variables (precipitation—P and temperature—T), simulation of hydrological models using corrected future climate projections and statistical analysis of chosen climatic and flow indices.

Hydrological modelling

The original GR4J hydrological model has four parameters and was developed by the French Institute CEMAGREF

(Perrin et al. 2003). More recent versions have also been developed with five and six parameters (Le Moine et al. 2005; Pushpalatha et al. 2012) to better simulate low and high flows. In this study we used GR4J with seven parameters. In addition to the four parameters of the original model representing maximum capacity of production store (x_1), groundwater exchange coefficient (x_2), 1-day-ahead maximum capacity of routing store (x_3) and time base of unit hydrograph UH1 (x_4), we used three snow-related parameters, namely TT—threshold temperature used to distinguish rainfall from snowfall, TTI—an interval within which precipitation is assumed to be a mix of rain and snow, decreasing linearly and CFMAX—degree-day factor. The inputs to the GR4J model include daily precipitation (Precip), mean air temperature (Temp) and potential evapotranspiration (Pet). The details of the GR4J hydrological model formulation are given in Piotrowski et al. (2017).

Although this extended version of GR4J has seven parameters instead of four, i.e. three parameters in the snow routine and four original parameters, the original name GR4J is retained in this paper.

For 18 selected catchments, the first year was used for the “warming-up” of the model to estimate the initial state variables. The remaining observations were divided into two time periods, two-third of the data length for calibration and one-third for validation, from 1971 to 2000 (calibration period) and from 2001 to 2009 (validation period). We applied the Nash–Sutcliffe criterion NS (Nash and Sutcliffe 1970) as an objective function for calibration of GR4J model for each selected Polish and Norwegian catchment. The optimal parameter sets of GR4J hydrological model were obtained by global optimization using differential evolution with global and local neighbourhoods DEGL (Das et al. 2009). The algorithm has been frequently used in hydrological modelling and has been demonstrated to be consistently better compared to other state-of-the-art evolutionary algorithms (Piotrowski et al. 2017).

Trend detection methods applied in the study

Parametric and nonparametric approaches are commonly used for identifying trends in hydrological and meteorological variables across the world (Ficklin et al. 2013; Chattopadhyay and Jha 2016; Chattopadhyay and Edwards 2016). The Mann–Kendall (MK) and modified Mann–Kendall (MMK) tests belong to the family of nonparametric tests. The other two tests applied here are based on the discrete wavelet transform (DWT) (Nalley et al. 2012; Nourani et al. 2015) and dynamic harmonic regression (DHR) (Young et al. 1999; Venier et al. 2012).

The Mann–Kendall and modified Mann–Kendall trend tests are rank-based tests of randomness against monotonic

trends (Burn et al. 2010; Abghari et al. 2013). Numerous studies have employed the MK (Chattopadhyay and Edwards 2016; Tosunoglu and Kisi 2016) and MMK (Giuntoli et al. 2013; Kibria et al. 2016). These are possibly the most widely used nonparametric tests for trend detection in hydrological and climatological studies (Mitof and Pravalie 2014; Jones et al. 2015). This is because they are not only simple to use, but they are also resilient to skewed distribution, missing values and values that fall outside the detection limit, and to the nonstationary nature of data (Chaouche et al. 2010; Jeneiova et al. 2014). However, the MK test does not account for the serial correlation that very often exists in hydrological time series (Yue and Wang 2004; Partal and Küçük 2006). The presence of serial correlation in a data set may lead to a misleading interpretation because it enhances the probability of finding a significant trend, when actually there is an absence of such a trend. Therefore, we applied the MMK test in cases where a significant correlation was present (Hamed and Rao 1998).

Extraction of long-term trends in precipitation and streamflow has been studied by many researchers (e.g. Nalley et al. 2013; Nourani et al. 2015) by means of discrete wavelet transform (DWT). The wavelet transform is an effective decomposition method that provides a way of analysing signals in both time and frequency domains. The DWT is used to isolate different periodicities embedded in a time series and to examine the composition of a signal. It helps to identify components that may be considered important in a signal, at their exact temporal location, which otherwise may not be clearly detected by the use of regular statistical tests alone (Nalley et al. 2013; Nourani et al. 2015). This is one of the most obvious strengths of the DWT because it gives a more complete picture of the dynamics contained in the signal being analysed. Trend analyses of hydrological processes using discrete wavelet transform and nonparametric Mann–Kendall methods have become very popular recently (Nourani et al. 2015; Nalley et al. 2012; 2013).

Dynamic harmonic regression (DHR) model is a powerful tool to extract nonstationary characteristics from analysed time series. In that model, temporal patterns in data are modelled within a stochastic state space formulation. Estimates of the states or time-varying parameters are then obtained using an optimal estimation method based on the Kalman filter. The DHR algorithm (Young et al. 1999) is available in the CAPTAIN toolbox for MATLAB™ (Taylor et al. 2007). It exploits an “unobserved component” model to optimally decompose the time series into long-term trend, periodic or quasi-periodic and “irregular” components, including the effect of other input variables if this is required. The method is statistically based, and so each component is extracted, together with associated measures of confidence (standard error bounds) that will allow for testing the significance of any changes in the components. The normal test is applied to assess the statistical significance of a trend (Hirsch et al. 1993; Mann and Whitney 1947). This test takes into account the uncertainty of trend estimates and is more robust than the other two tests applied in this study.

Results

The trend analysis was performed using the selected hydroclimate indices for each of ten Polish and eight Norwegian catchments in the projection period (1971–2100). Additionally to 130-year-long time series, we used three 30-year-long subperiods, the reference period (1971–2000), the near-future period (2021–2050) and the far-future period (2071–2100) and we estimated the relative changes of hydroclimatic extremes in the future with respect to the reference period. The latter approach is commonly used in the climate change impact studies instead of a long-term trend analysis on the grounds that in this way the nonstationarity of time series can be neglected. The main drawback of that approach lies in the dependence of the results on the time horizon used (Alfieri et al. 2016).

Fig. 3 General flow chart of trend estimation in extreme indices derived from hydroclimatic projection

Table 4 The NSE results of calibration and validation for Polish and Norwegian catchments; Cali denotes calibration stage, Vali denotes validation stage, CML denotes catchment list

CML	Cali	Vali
Dunajec	0.78	0.81
Wisla	0.72	0.76
Biała	0.79	0.74
Nysa	0.73	0.7
Oleśnica	0.66	0.66
Łasica	0.48	0.34
Narewka	0.72	0.6
Flinta	0.62	0.62
Myśla	0.62	0.52
Guber	0.62	0.73
Ardal	0.85	0.76
Eggedal	0.66	0.72
Fustvatn	0.56	0.57
Krinsvatn	0.77	0.81
Myglevatn	0.81	0.76
Polmak	0.79	0.79
Viksvatn	0.62	0.64
Atnasjo	0.71	0.55

In the analysis we used an ensemble of climate model outputs. Following the discussion presented by Knutti et al. (2010), there is no recommended approach to model averaging. The decision whether model averaging should be performed and which method should be used for averaging depends on the specific application. Therefore, in the present study both combined and individual ensembles are applied. A part of the analysis related to the comparison of different trend estimation approaches using 130-year-long time series is based on a combined ensemble model output. We combine seven projected hydroclimatic variables from seven GCMs/RCMs using a simplified form of the total variation approach (Sain and Furrer 2010). This combining strategy has an advantage of considering the variance and correlation among the climate model output.

The comparison of changes of extreme indices within the 30-year windows for the near-future and far-future periods in relation to the reference period, is performed using individual climate ensembles which are equally weighted. The examples are taken from a case study of the ten Polish and eight Norwegian catchments. We illustrate the results using two catchments, one from Poland and one from Norway. The choice of the catchments was dictated by their typical for each country behaviour, but otherwise was arbitrary.

Hydrological modelling: calibration and validation stages

The results of calibration range from 0.48 to 0.79 of NS for the Polish catchments and from 0.56 to 0.85 for the

Norwegian catchments. This shows a very good agreement between the observed and estimated flows. Table 4 shows the results of calibration and validation of the Polish catchments. The acceptable value of Nash–Sutcliffe criterion—based on daily flow in lowland and mountainous catchments—may vary because of the error square value in the formulation. Therefore, in lowland area (e.g. Łasica catchment) a NS of ≥ 0.4 is generally accepted to reflect a reasonable model performance for various purposes (ecological, water resource management, impact analysis, irrigation).

As an illustration, the hydrographs of the observed and modelled flow data for the validation period in 2005 for one Polish (Narewka) and one Norwegian (Ardal) catchments are presented in Fig. 4. Narewka and Ardal results are shown on the left and right panels, respectively. The figure shows a good agreement, except for base flow which is not always well represented. This may originate from the fact that the NS criterion used for the calibration puts more focus on medium to high flows (Gupta et al. 2009). Altogether, the validation results for the GR4J model are of the same accuracy as the results for the HBV model presented in Romanowicz et al. (2016), where the same catchments from Poland and Norway were analysed.

Projected hydroclimatic indices

The multi-model climate projections are used to simulate streamflow projections for the selected catchments using the calibrated GR4J model. The simulated annual maximum and mean daily flows during the period 1971–2100 for seven climate projections under the RCP4.5 emission scenarios are shown in Fig. 5. The Narewka flows are presented in the left panel, and the Ardal flows are shown in the right panel. Shaded areas present ensemble spreads: light red—for the reference period 1971–2000; light green—for the future period 2001–2100; blue lines show ensemble means of annual maximum daily flow (AmaxDF) and annual mean daily flow (AmeanDF). The yellow line shows a 10-year moving average. The catchment response to an external forcing depends on the catchment flood regime, the elevation, land cover and its spatial location. Narewka has a snow-dominated flood regime and is a lowland catchment. Ardal is rainfall-dominated. The shaded area reflects the flow variability related to the climate model ensemble, but it gives only a qualitative description of the trends in projections. The visual inspection gives an impression of decreasing annual maximum flows in Narewka and increasing trends in Ardal. The statistical tests presented in the following part of the section will tell us whether the visual impressions are quantitatively justified.

Fig. 4 Validation of hydrological model GR4J for the Narewka (left panel) and the Ardal catchment (right panel)

Fig. 5 Annual maximum daily flow for Narewka (left) and Ardal (right) upper panels; lower panels show annual mean flow for Narewka (left) and Ardal (right); projections for 1976–2100 based on seven climate models

Projected changes in the selected indices of temperature, precipitation and flow in two future periods (2021–2050 and 2071–2100)

The aim of this section is an illustration of the influence of climate model variability on changes of extreme indices

within a 30-year window. In order to compare differences in the hydroclimatic variables between the baseline condition and future conditions (reference period 1971–2000, near-future 2021–2050 and far-future 2071–2100), the annual maximum, minimum and mean precipitation in a relative format (%), temperature in absolute change (°C)

and flow in a relative format (%) are compared. Figure 6a–c describes changes derived for the Polish catchments, and Fig. 7a–c shows the results for the Norwegian catchments. The figures present the box plots showing the median and 0.25 and 0.75 quantiles from the seven GCM/RCM climate projections listed in Table 2. In this section all the ensembles are treated as equally likely. According to the projected changes in the different climate indices, climate change has the potential to modify future flow characteristics remarkably across the country in near- (2021–2050) and far (2071–2100)-future periods (Figs. 8, 9).

The changes of precipitation show much higher variability than temperature changes (Figs. 6a, b). Increases of annual maximum, mean and minimum air temperature were observed for all studied catchments, with median annual mean increases from 1.2 to 3.0 °C, which is consistent with the results presented by Romanowicz et al. (2016).

The mean changes of annual maximum precipitation show even up to 250% decrease either in near- or in far-future periods. On the average, the mean changes of annual mean precipitation in Polish catchments have varying sign

in the near future and 20–30% increase of mean precipitation in the far future (Fig. 6b).

Relative flow changes for annual maximum and mean flows are shown in Fig. 6c. As expected, the changes of annual maximum flows have the largest spread, reaching up to 700–800% for the Łasica and the Nysa catchments. Myśla is also characterized by large relative changes of maximum flow values, in particular for the far-future period.

Figure 7a–c presents the results of analysis of relative trend changes for the Norwegian catchments. Whereas the changes in temperature have similar positive trends in the near and far future, the variability among the catchments is more uniform in the Polish than in the Norwegian catchments. The largest annual maximum temperature changes (upper panel of Fig. 7a) are projected in Fustvatn catchment (over 10 °C for one of the ensemble members of climate projections). On the other hand, the largest changes of mean annual temperature (middle panel of Fig. 7a) are projected for the Polmak catchment. Also projected annual minimum temperature changes (lower panel of Fig. 7a) are

Fig. 6 a Absolute annual maximum, mean and minimum temperature changes in the near and far future periods in the Polish catchments. b Relative changes of annual maximum precipitation (upper panel) and mean precipitation (lower panel) in the near and far

future periods in the Polish catchments. c Relative changes of annual maximum flow (upper panel) and annual mean flow (lower panel) in the near and far future periods in the Polish catchments

Fig. 7 **a** Annual maximum, mean and minimum temperature absolute changes in the near and far future periods in the Norwegian catchments. **b** Annual maximum and mean relative precipitation

changes in the near and far future periods in the Norwegian catchments. **c** Annual relative maximum and mean flow changes in the near and far future periods in the Norwegian catchments

the largest in Polmak and are in the range between -5 and 15 °C.

Presented in Fig. 7b, upper panel, annual maximum precipitation indices show the largest variability for the Fustvatn catchment for the near future. In the far future the decrease of annual maximum and mean precipitation is predicted in the Fustvatn and Viksvatn catchments.

Annual maximum and mean flow changes shown in Fig. 7c vary between catchments and periods. As mentioned before, those changes are probably related to changing flood regimes in the catchments caused by rising temperatures. Most of the Norwegian catchments show increased annual maximum flow in the near- and far-future periods except in the Polmak, where it decreases. Most notably catchments like Ardal, Eggedal, Krinsvatn, Myglevatn and Atnasjo exhibit small to moderate increases in annual maximum flow. Fustvatn shows large increase of annual maximum flow in the near future and no change/decrease in the far future. This behaviour is consistent with large variability of precipitation projections in this catchment shown in Fig. 7b. The annual mean flows show smaller changes, in particular in comparison with the changes projected in Polish catchments.

Autocorrelation and seasonality in the selected projected hydroclimatic indices

In this study, the autocorrelation of each hydroclimatic time series was examined and correlograms were produced. Autocorrelation coefficients are commonly used to examine whether time series exhibit nonrandom characteristics. If a serial correlation exists in a time series, it increases the likelihood of rejecting the null hypothesis of no trend, when in fact the null hypothesis should be accepted in the original Mann–Kendall test. This is because the variance of the Mann–Kendall test statistics is underestimated. In Table 5, the letter N denotes time series without serial correlation and the letter Y represents time series with a significant serial correlation.

Temporal trends in the projected hydroclimatic variables

Four trend detection methods (MK, MMK, DWT, DHR) have been applied to estimate trends of future hydroclimatic extreme indices for the 1971–2100 period. The results for two catchments, one Polish catchment Narewka

Fig. 8 a DHR-based trend results for the Narewka catchment; results for maximum and mean flows [m^3/s] and maximum temperature [$^{\circ}\text{C}$] are shown in the left panels and maximum, maximum and sum precipitation [mm] are shown in the right panels; red dots denote modelled data; black continuous line denotes the DHR model simulation and red line denotes estimated trend; 95% and 5% confidence limits for trend are denoted by dashed lines. **b** DHR-based

trend results for the Ardal catchment; results for maximum and mean flows [m^3/s] and maximum daily temperature [$^{\circ}\text{C}$] are shown in the left panels and maximum and sum precipitation [mm] are shown in the right panels; red dots denote modelled data; black continuous line denotes the DHR model simulation and red line denotes estimated trend; 95% and 5% confidence limits for trend are denoted by dashed lines.

Fig. 8 continued

and one Norwegian catchment Ardal, are presented for graphical illustration of projected annual maximum/mean flow, sum/maximum precipitation and maximum temperature.

The results of the DHR-based trend estimation illustrated in Figs. 8a, b show differences in projected trends for the extreme and mean annual flows for the

Narewka and Ardal catchments. The differences are due, among other reasons, to different flow regimes in both catchments, snow melt dominated in the Narewka and rainfall-dominated in the Ardal catchment. With increasing maximum and mean rainfall and decreasing snow-fall following increasing temperatures, the flow regimes change in those catchments which were

previously snow-dominated. These changes may result in changes of dominant modes of catchment behaviour and may cause the nonstationarity of model parameters (i.e. the parameters selected in different from modelled flow conditions may not be adequate in future climatic conditions).

Figures 9a, b show trends of the projected time series using the discrete wavelet components for the Polish and Norwegian catchments. The trend, wavelet details and original data of the wavelet components are shown by blue continuous lines, light blue continuous lines and red dots, respectively. The DWT results confirm the DHR results that the annual maximum daily flows increase in the Narewka catchment (Fig. 9a), whilst the temporal slope

change is more clearly visible for the DHR than the DWT. In Fig. 9b, the results of the DWT analysis for the Ardal catchment are presented. Here we can also see the consistency between the results of trend analysis using both approaches.

The annual maximum precipitation, annual sums of precipitation and annual daily maximum temperatures show similar trends under DWT and DHR approaches for both catchments. The annual mean flow for Narewka shows larger “visual” trend in the DWT approach than the DHR. The main difference consists of the presence of uncertainty estimates of the time-variable mean (so-called trend) for the DHR approach. This difference has very important implications in detecting the existence of trend

Fig. 9 a DWT-based trend results for the Narewka catchment; results for annual sum precipitation, annual maximum daily precipitation [mm] and annual mean temperature [°C] are shown in the left panels and mean and maximum annual flows [m³/s] are shown in the right panels; red dots denote modelled data; dark blue line denotes estimated trend, light blue lines denote wavelet components. **b** DWT-

based trend results for the Ardal catchment; results for annual sums and annual maximum precipitation [mm] and annual maximum temperature [°C] are shown in the left panels and mean and maximum annual flow [m³/s] are shown in the right panels; red dots denote modelled data; dark blue line denotes estimated trend, light blue lines denote wavelet components

Fig. 9 continued

Table 5 Autocorrelation result at lag 1: N presents no autocorrelation, whereas Y is existence of autocorrelation in time series

	Flow		Pr		Temp	
Poland/Norway	Max	Mean	Sum	Max	Mean	Max
C1/CC1	N/N	N/N	N/Y	N/N	Y/Y	Y/Y
C2/CC2	N/N	N/N	N/N	N/N	Y/Y	N/Y
C3/CC3	N/Y	N/N	N/N	N/Y	Y/Y	Y/N
C4/CC4	N/N	N/N	N/N	N/Y	Y/Y	Y/Y
C5/CC5	N/N	N/Y	N/N	Y/N	Y/Y	Y/Y
C6/CC6	Y/N	Y/N	Y/N	N/N	Y/Y	Y/Y
C7/CC7	N/N	Y/N	N/N	N/N	Y/Y	N/Y
C8/CC8	N/N	N/Y	N/N	N/N	Y/Y	N/Y
C9/–	N/–	Y/–	N/–	N/–	Y/–	Y/–
C10/–	N/–	Y/–	Y/–	N/–	Y/–	Y/–

Pr denotes precipitation, Temp temperature

using statistical tools of hypothesis testing. Namely, the DHR-based low-frequency nonparametric component is derived together with its error estimates, which have the form of a zero-mean white noise (Young et al. 1999). This enables the application of the normal test to find the significance of changes in mean values of that component taking into account their variance. Taking into account the uncertainty of trend estimates explains why the DHR-based trend estimates are the most conservative of all the other techniques applied.

Trend test in the selected variables

Tables 6 and 7 show the results of trend analyses of all selected indices using four techniques, DHR, DWT and either Mann–Kendall or modified Mann–Kendall, for the Polish and Norwegian catchments. Trends in selected

Table 6 Trends of streamflow and precipitation indices in ten selected catchments in Poland.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
DHR/DWT/MMK										
AMeanT	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
ASumP	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
AMaxP	0/↑/↑	↑/↑/↑	↑/↑/↑	0/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
AMaxQ	0/↑/↑	0/↓/↓	0/↓/↓	0/↑/↑	0/↑/↑	0/↑/↑	0/0/0	0/↑/↑	↑/↑/↑	0/↑/↑
AMeanQ	↑/↑/↑	↑/↑/↑	↑/↑/↑	0/0/0	↑/↑/↑	↑/↑/↑	↑/↑/↑	0/0/0	↑/↑/↑	↑/↑/↑
MAXQ1	↑/↑/↑	0/↓/↓	0/↓/↓	↑/↑/↑	0/↑/↑	0/↑/↑	0/↓/↓	0/↓/↓	↑/↑/↑	↓/↓/↓
MAXQ2	0/0/↑	↑/↑/0	0/↑/↑	0/0/0	↑/↑/0	0/↑/↑	↑/↑/↑	0/↑/↑	↑/↑/↑	0/0/↑
SSP1	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
SSP2	0/↓/0	0/↓/0	0/0/↑	0/↓/↓	↑/↑/↑	↑/↑/↑	0/↑/↑	0/0/0	0/↑/↑	0/↑/↑

DHR/DWT/modified Mann–Kendall Z values are shown. Arrows show the direction of trend significant at a level of $p < 0.05$

Table 7 Trends of streamflow and precipitation indices in eight selected catchments in Norway

	CC1	CC2	CC3	CC4	CC5	CC6	CC7	CC8
DHR/DWT/MMK								
AMeanT	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
ASumP	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
AMaxP	0/↑/↑	↑/↑/↑	0/↑/↑	↑/↑/↑	0/↑/↑	↑/↑/↑	0/↑/↑	0/↑/↑
AMaxQ	↑/↑/↑	0/↓/0	↑/↑/↑	↑/↑/↑	↑/↑/↑	↓/↓/↓	↑/↑/↑	↑/↑/↑
AMeanQ	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
MAXQ1	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑	↑/↑/↑
MAXQ2	0/↓/0	0/↓/↓	↓/↓/↓	↑/↑/↑	↑/↑/↑	↓/↓/↓	↓/↓/↓	↑/↑/↑
SSP1	↑/↑/↑	↑/↑/↑	0/↑/0	0/0/0	↑/↑/↑	↑/↑/↑	0/↑/↑	↑/↑/↑
SSP2	0/↑/↑	0/↑/↑	↑/↑/↑	↑/↑/↑	0/↑/↑	↓/↓/↓	↑/↑/↑	0/↑/0

DHR/DWT/modified Mann–Kendall Z values are shown. Arrows show the direction of trend significant at a level of $p < 0.05$

indices of precipitation, temperature and flow projections are estimated for the whole period 1971–2100. Results of the DHR analysis of annual maximum flows for Polish and Norwegian catchments are presented in the supplementary material. Tables 6 and 7 indicate that there are differences in the results for the individual hydroclimatic variables and that there are differences in the results for different catchments.

The results of the four applied trend detection methods, MK, MMK, DHR and DWT, are consistent in most cases. All methods show positive trend for annual mean temperature and annual sums of precipitation for both Polish and Norwegian catchments. Annual maximum precipitation shows positive trend for DWT and MK, MMK, but DHR shows no trend for that index in Dunajec and five other Norwegian catchments (Ardal, Fustvatn, Myglevatn, Viksvatn and Atnasjo).

The DHR shows no statistically significant trend in annual maximum flows in Polish catchments, except for Myśla, where it is positive. The other methods are less restrictive and show mostly positive trend in that index in

Polish catchments with the exception of Wisla and Biala, where the negative trend is shown by those two approaches. Of the Norwegian catchments, Polmak has shown the negative trend in annual maximum flow by all techniques tested. The explanation for a negative trend may lie in a changing flow regime, as already mentioned. That catchment has snow-melt-driven flood regime, and similar changes were observed already by Madsen et al. (2014). However, according to the DHR and DWT, the snow-melt-based Atnasjo shows a positive trend detected in this catchment by all approaches tested. The other catchment that shows no or negative trend in the annual maximum flow is Eggedal, with a mixed flow regime. Therefore, more research is required to explain the annual maximum flow changes in those particular catchments.

Annual mean flows were included for the comparison with the extreme flows. All the methods show that Nysa and Flinta have no trend in annual mean flow and the rest of the catchments have positive trends. Therefore, some Polish catchments show no statistically significant positive trend in annual maximum flow values, whilst the mean

flows are increasing. These are Narewka according to all three methods tested and the rest of the Polish catchments that have negative trend according to the DWT and MMK, with except of Myśla.

The seasonal maximum temperature, flow and precipitation indices are more variable, which is not surprising and indicates interannual changes in climatic patterns. All winter annual maximum flow trends are positive for the Norwegian catchments. Trends are also positive for the Dunajec, Nysa and Myśla, but negative for the Guber. Annual maximum summer flows have mostly positive trends for Polish catchments, but the trends are mixed for the Norwegian catchments. They are positive only for Krinsvatn, Myglevatn and Atnasjo for all the methods applied, and they are nonpositive (zero or negative) for the rest of the catchments. The seasonal precipitation patterns are not always consistent with the flow patterns. Namely, winter maximum precipitation and flow trends have opposite direction in Wisła, Narewka, Flinta and Guber catchments in Poland. On the other hand, summer maximum precipitation trends have opposite directions in Wisła and Nysa in Poland and Eggedal and Viksvatn in Norway. In a summary, there is a visible tendency for the change of flood regime from winter to summer period, which can be explained by the rising air temperatures.

In this study, the DWT and DHR approaches have clearly demonstrated how timescale information can be extracted from the data. By and large, the DHR method is more discriminating, which shows in the larger amount of “0”, i.e. “no trend” results. The possible changes of flood regime require further analysis of the mechanisms of those changes.

Meresa et al. (2016) concluded that climate change is likely to have a widespread impact on future flow and precipitation in Poland. In our study, highest impacts can be found in the north-west part of Poland (Myśla, Flinta), which is likely to suffer from increased annual maximum flow. Interestingly, the annual maximum flow trends do not necessarily coincide with the changes of annual mean flows. Increases in annual precipitation indices were observed in most catchments in this study, but they are not necessarily statistically significant. In the Norwegian catchments, large changes are expected in the north and north-west parts of the country, with the north getting wetter but with decreasing annual maximum flows and the north-west, becoming more prone to floods.

Discussion

The main aim of this research was to present the results of trend analysis of future extreme temperature, precipitation and flow projections for selected Polish and Norwegian

catchments using standard and new approaches. Firstly, the changes of extreme indices were estimated using a 30-year window, for so-called near- and far-future periods. Secondly, the 130-year-long projections were analysed for trend using four different trend estimation techniques.

The trend analyses using 130-year-long projections were performed for weighted mean simulations from the seven GCM/RCM models. The four different techniques of trend assessment were applied in order to check the consistency and assure the reliability of the results. In the 30-year window approach, each GCM/RCM projection was treated equally likely and the spread of the resulting changes was shown together with their mean values.

Due to the differences in the approaches based on different time horizons, only qualitative comparison of changes in hydrometeorological indices is possible.

Comparison of projected 30-year changes of hydroclimatic indices with the trend analysis performed on the entire 130 years presented in Table 6 for Polish catchments and Table 7 for the Norwegian catchments shows consistency in the estimated precipitation trends. According to the long-term trend analysis all the catchments experience increased precipitation in the far future.

The results for the annual maximum flow changes are not giving the same message. For example, in Table 6, positive trends of annual maximum flows are shown by all three methods only for Myśla and no trend is shown for Narewka. The DHR method shows no trend for the rest of the catchments. The other methods show negative trends for Biała and Wisła and positive trends for the other catchments. These differences may result from multiple reasons. Firstly, the 30-year window catches multidecadal variability in time series and an arbitrary definition of start and end years of those 30-year periods introduces certain subjectivity into the assessment of changes. The other possible explanation lies in a very large uncertainty of 30-year window trends which causes the decrease of the power of statistical tests applied. These results indicate that further research should be undertaken to make the trend assessments more robust but also to understand the nature of its variability.

For Norwegian catchments the DHR-based long-term trend estimates from Table 7 show no trend in annual maximum precipitation for these two catchments, whilst the DWT and MMK test shows the positive long-term trends for both the annual maximum and mean precipitation. The rest of the catchments show positive trends in precipitation by both long-term and 30-year period assessment approaches.

It is interesting to note that Polmak shows increase of annual mean flows, whilst the annual maximum flows are decreasing in that catchment. These results are consistent with the long-term trend estimates.

It should be noted that the relative variability expressed in the form of relative changes of hydroclimatic indices does not adequately represent the actual amounts of water (Meresa and Romanowicz 2016; Piniewski et al. 2017) and does not allow for the intercomparison of results between the catchments. This is the reason why the standardized indices (e.g. standardized runoff index) were introduced (Shukla and Wood 2008). The comparison of changes between catchments would give different outcomes if they were expressed as the absolute difference between future horizons and the reference period (e.g. in mm). The reason for this is a large variability in runoff coefficients and precipitation among catchments.

Conclusions

This study assessed the trend of projected hydroclimatic indices and impacts of projected climate change on hydrological extremes in ten catchments from Poland and eight catchments from Norway. Projected changes of extreme precipitation and streamflow characteristics were analysed using the GR4J hydrological model simulations and bias-corrected EUR11 RCP45 climate model projections. The results can be summarized in the following points.

1. Two substantially different approaches to estimate changes in projections of extreme hydroclimatic indices are applied. The first approach follows the standard climate change impact assessment consisting of comparison of the equally weighted ensemble of extreme indices estimated within the 30-year windows, the reference period 1971–2000, the near-future 2021–2050 and the far-future 2071–2100. Choice of the 30-year window is motivated by the assumption that stationarity of the processes can be assumed within those 30-year periods (i.e. smooth and slow climate change impact on hydrometeorological processes is assumed). However, the 30-year periods can include some interdecadal variability that affects the results.
2. Within the first, standard, approach, the near- and far-future projections of extreme indices were compared with the reference period. The relative changes of annual maximum and mean flows estimated using the 30-year periods, so-called near and far future related to the reference period, are much more variable than the trends obtained using the 130-year periods. Some of the short-term changes may be accommodated within the long-term variability, but the other cannot be explained. Further studies are needed to estimate the uncertainty of the relative changes of extreme indices and their dependence on the time horizon.
3. In the second approach, being the main aim of this study, the 130-year-long weighted ensemble mean of extreme indices is used to derive trends in hydroclimatic extreme indices and this approach is referred to as a long-term trend estimation.
4. Within the second approach, four trend estimation methods were applied, including the DWT, DHR and the MK and MMK tests. The results in projected future temperature across all catchments showed a steady and significant increase. On the other hand, the other indices derived from precipitation and streamflow show both positive and negative trends. All four techniques showed consistent results, with small differences explained by the differences of assumptions and the methodology. In particular, the DHR-based trend assessment exhibits a conservative character resulting from taking into account the uncertainty of the derived trend estimates. The comparison of trend estimates for annual mean and maximum flows shows that in some catchments a positive trend in mean flows is not necessarily followed by a positive trend in annual maximum values. Among Polish catchments these are Wisła, Biała and Narewka and Eggedal and Polmak among the Norwegian catchments, which all have nonpositive trend of annual maximum flows, whilst their annual mean flows show positive trends.
5. The seasonal trend estimates were limited to winter and summer maximum flows and sums of precipitation. Some interesting patterns of opposite trends between seasonal sums of precipitation and maximum flows were found for both Polish and Norwegian catchments, indicating that related to temperature snow melt may play an important role in catchment hydrology.
6. The qualitative comparison of the estimates of changes of indices based on 30-year hydroclimatic projections in the near and far future shows that those changes are not substantiated by the long-term (130-year) trend analysis.

Finally, the results obtained present some baseline information which can serve as grounds for basing the water resources design and planning within the watersheds covered by the study area. Despite catchment to catchment variability, it can be concluded that the range of changes is mainly related to changing flow regimes in the catchments.

Acknowledgements This work was supported by the project CHIHE (Climate Change Impact on Hydrological Extremes), carried out in the Institute of Geophysics Polish Academy of Sciences, funded by Norway Grants (Contract No. Pol-Nor/196243/80/2013) and partially supported within statutory activities No 3841/E-41/S/2017 of the Ministry of Science and Higher Education of Poland.

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