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The probabilistic hydrological model MARCS (MARkov Chain System): the theoretical basis for the core version 0.2

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Abstract. A question of environmental risks of social and economic infrastructure has become apparent recently due to an increase in the number of extreme weather events. Extreme runoff events include floods and droughts. In water engineering extreme runoff is described in terms of probability, and uses methods of frequency analysis to evaluate an exceedance probability curve (EPC) of runoff. It is assumed that historical observations of runoff are representative for the future; however trends in observed time series doubt this assumption. The paper describes an Advance Frequency Analysis (AFA) approach to be applied to predict future extreme runoff. The approach combines traditional methods of hydrological modelling and frequency analysis, and results in a probabilistic hydrological model Markov Chain System (MARCS). The MARCS model simulates statistical estimators of a multi-year runoff to perform future runoff projections in probabilistic form. Projected statistics of meteorological variables available in climate scenarios force the MARCS model. This study introduces a new model core (version 0.2), and provides an user guide as well as an example of the model set up for a single case study. In this case study, the model simulates projected exceedance probability curves of annual runoff under three climate scenarios. The scope of applicability and limitations of the model are discussed.

Introduction

Streamflow runoff serves water resources for humans, food production and energy generation, while risks of water-sensitive economics are usually connected to runoff extremes. In fact, the runoff extremes are always connected to a human activity since they are not existing in a natural water cycle. Engineering science considers the runoff extremes as critical values of runoff leading to damage of infrastructure or water shortages, and introduces the extremes in terms of probability. In particular, in water engineering the runoff extremes are evaluated from tails of exceedance probability curves to be used in risk assessment of water infrastructure and decision-making in cost-lost situations (Mylne, 2002; Murphy, 1977, 1976). The exceedance probability curve (EPC) of multi-year runoff allows estimation of the runoff extremes and supports designing of building constructions, bridges, dams, withdrawal systems, *etc*.

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Modern hydrology uses two basic approaches to evaluate the runoff extreme of particular exceedance probability: conceptual modelling (Lamb, 2006) and a frequency analysis (Kite, 1977; Benson, 1968; Kritsky and Menkel, 1946). In the conceptual-modelling approach, synthetic runoff series are simulated from meteorological series, and are then used to calculated the runoff of chosen exceedance probability (Seibert, 1999, Arheimer and Lindström, 2015). In the frequency-analysis approach, historical yearly time series of runoff are used to evaluate statistical estimators (*i.e.* mean value, coefficient of variation and coefficient of skewness). These estimators are further applied to model the EPC of runoff, and to calculate the runoff of chosen exceedance probability (van Gelder, 2006). These runoff values support designing roads, dams, bridges or water-withdrawal stations in an assumption that the risks during infrastructure's operational period in the future are equal to the risks estimated from the past. It means, the runoff extremes are simply extrapolated for the next 20-30 years on an assumption that the past observations are representative for the future or a “stationarity” assumption.

A number of weather extremes including hurricanes, wind, rain and snow storms, floods and droughts has increased (Vihma, 2014; Wang and Zhou, 2005, Manton et al., 2001). Historical time series of many climate variables evident trends, which are statistically significant, and the series of streamflow runoff are among others (Madsen et al., 2013; Wagner et al., 2011; Dai et al., 2009). Rosmann et al. (2016) apply the Mann–Kendall Test to analyse a time series of daily, monthly and yearly river discharges for last four decades. The highest number of the trends are detected for the yearly time series of annual runoff. The reasons of these trends in historical observations may be linked to climate change (Milly at al., 2008; 2005) or to uncertainties inherent in techniques applied to estimate basic statistics from observations of limited lengths (Serinaldi and Kilsby, 2015). The statistically significant trends are founded on historical time series, thus the water engineers and managers are motivated to revise a basic “stationarity” assumption behind the infrastructures’ risk assessment since the past observations are not representative for the future (Madsen et al., 2013; Kovalenko, 2009; Milly at al., 2008).

In this study, an approach combing methods of the conceptual modelling and frequency analysis to estimate the runoff extremes in changing climate was used. The approach adapts a theory of stochastic systems to water-engineering practice, and it is further named as an Advanced of Frequency Analysis (AFA). In water engineering, the approach is introduced by Kovalenko (1993) relying on theory of stochastic systems (Pugachev et al., 1974). The idea behind the approach is to simulate statistical estimators of multi-year runoff (annual, minimal and maximal) from statistical estimators of precipitation and air temperature available in projections of climate (Budyko and Izrael, 1991). The simulated statistical estimators of runoff are further used to model exceedance probability curves with distributions from the Pearson System (Pearson, 1895). Kovalenko (1993) suggests modelling the EPCs within the Pearson Type III distribution since it is recommended in the Russian guideline for water engineers (Guideline, 1984). However, the distribution can be also chosen by fitting (Laio et al., 2009) or defined in accordance with local hydrological guidelines (Bulletin 17-B, 1982).

A linear “black-box” model with stochastic components (or “linear stochastic filter”) is suggested as a catchment-scale hydrological model (Kovalenko, 1993). For this linear model, the theory of stochastic systems provides methods of a direct simulation of probability distributions for a random process (Pugachev et al., 1974). The theory of stochastic systems is applied to analyse and predict runoff extremes on various time scales ranging from days (Rosmann and Domínguez, 2017), season (Domínguez and Rivera, 2010; Shevnina, 2001) to decades (Shevnina et al., 2017; Kovalenko, 2014, Viktorova and Gromova, 2010). The AFA approach is a simplification of the theory of stochastic systems on a decadal scale. Kovalenko et al., (2010) presents a summary for water engineers on how to utilize climate scenarios in calculations of the future exceedance probability curves of multi-year runoff. This guideline presents the simplest version of the AFA, and the future EPCs are modelled from two statistical estimators (mean value and coefficient of variation).

The AFA has been suggested more than 20 years ago, however the full description of this approach is still not published in English. Moreover, the previous publications in Russian contain many typewriting mistakes in formulas (Kovalenko et al., 2014; Kovalenko et al., 2006), and it makes understanding troublesome even for native Russians. In this paper, a theory and assumptions of the AFA approach were formulated "step-by-step" (Sec. 1), and formulas behind the core (version 0.2) of the probabilistic hydrological model MARCS (MARkov Chain System) were accepted. Recently, a new model core allowing prediction of skewness parameter of the Pearson Type III distribution (Sec. 2). An example of the model set up, forcing and output was given for a case study of Iijoki river (Sec. 3). The main features of the MARCS model were formulated in Discussions to define the scope of applicability and limitations of the model in Conclusion.

1 Assumptions behind the Advance of Frequency Analysis

The Advance of Frequency Analysis is based on the theory of stochastic systems, specifically, the Fokker-Plank-Kolmogorov equation (FPK), which is simplified to a system for three statistical moments (Pugachev et al., 1974; Rogdestvensky and Saharyk, 1974). The time series of annual runoff is considered as realization of a random process Markov chain type assumed to be "stationary". It means that the statistical estimators (mean, variance and skewness) do not change over period considered. The statistical estimators are used to model an exceedance probability curve of annual runoff within the Pearson Type III distribution. The AFA approach is developed with an assumption of "quasi-stationary" (Kovalenko et al., 2010, Kovalenko, 1993). The "quasi-stationary" assumption suggests that the statistical estimators of multi-year runoff are different for two periods (reference and projected). For the reference period, the statistical estimators are evaluated from historical yearly time series of runoff. For the projected period, the statistical estimators of runoff are simulated based on an output of global- or regional-scale climate models under any climate scenario.

1.1 Linear filter stochastic model

Models replace a complicate hydrological system by maths abstractions, and aim to reveal spatial and temporal runoff features which are important depending on goals of study. Among others, "black box" hydrological models consider a river basin as a dynamical system with lumped parameters. These models are "based on analysis of concurrent inputs and temporal output series" (WMO-№168, 2009), and transform series of meteorological variables (precipitation, air temperature) into series of runoff. Both input and output series are functions of time (WMO-№168, 2009):

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$$a_n(t)\frac{d^nQ}{dt^n}+a_{n-1}(t)\frac{d^{n-1}Q}{dt^{n-1}}+...+a_1(t)\frac{dQ}{dt}+a_0(t)Q= \\ =b_n(t)\frac{d^nP}{dt^n}+b_{n-1}(t)\frac{d^{n-1}P}{dt^{n-1}}+...+b_1(t)\frac{dP}{dt}+b_0(t)P \quad , \tag{1}$$

where Q is the runoff in volumetric flow rate, P is the precipitation in volumetric flow rate (rain, snow melt); and the coefficient a_i and b_i are the empirical parameters of a translating system. The solution to Eq. (1) for zero initial conditions gives (WMO-№168, 2009):

$$Q(t)=\int_0^t h(t,\tau)P(\tau)d\tau \,, \tag{2}$$

where the function $h(t,\tau)$ represents a response of a river basin at time *t* to a single portion of precipitation at time τ . In the AFA approach, a river basin is considered as a linear system transforming the annual precipitation into the annual runoff:

$$a_1(t)\frac{dQ}{dt}+a_0(t)Q=b_0(t)P \ . \tag{3}$$

On the other hand, a river basin can be considered as a linear system with stochastic components in the input function and the model parameter:

$$dQ=[-(\bar{c}+\tilde{c}(t))Q+(\bar{N}+\tilde{N}(t))]dt \ , \tag{4}$$

where $a_0(t)=\bar{c}+\tilde{c}(t)$ is the stochastic parameter of the system (a “noised” watershed physiography, the inverse of runoff coefficient in Kovalenko, (1993)); $b_0(t)P=\bar{N}+\tilde{N}(t)$ is the stochastic input for the system (a “noised” precipitation), and $a_1=1$. The stochastic components of $\tilde{c}(t)$ and $\tilde{N}(t)$ are the Gaussian “white noise” with zero means, and their intensities are $G_{\tilde{c}}$, $G_{\tilde{N}}$. The intensities are mutually correlated as $K_{\tilde{c}\tilde{N}}(\tau)=E(\tilde{c}(t)\tilde{N}(t+\tau))=G_{\tilde{c}\tilde{N}}\delta(\tau)$.

1.2 Fokker-Plank-Kolmogorov equation and simplifications

The Fokker-Plank-Kolmogorov equation can be applied to simulate the probability density function (PDF) for the stochastic *Q(t)* in Eq. 4 (Kovalenko, 1993; Pugachev, 1974):

$$\frac{\partial p(Q,t)}{\partial t}=-\frac{\partial}{\partial Q}(A(Q)p(Q,t))+0.5\frac{\partial^2}{\partial Q^2}(B(Q)p(Q,t)) \ , \tag{5}$$

where $p(Q,t)$ is the PDF of Q at time t; and the drift coefficient ($A(Q)$) and diffusion coefficients ($B(Q)$) are calculated as follows (Kovalenko, 1993; Pugachev, 1974):

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$$A(Q)=-(\bar{c}-0.5G_{\tilde{c}})Q-0.5G_{\tilde{c}\tilde{N}}+\bar{N}\ , \tag{6}$$

$$B(Q)=G_{\tilde{c}}Q^2-2QG_{\tilde{c}\tilde{N}}+G_{\tilde{N}}\ . \tag{7}$$

The analytical solution of Eq. (5) is difficult and not always needed for practical applications in water engineering since the PDFs of runoff are modelled from a set of statistical estimators, and moments are from, among others, van Gelder et al. (2006). The PDFs are described with the set of moments $m_k=\int_{-\infty}^{+\infty}Q^k p(Q,t)\,dQ$ (where k is number of the moment, and k –> ∞). To obtain the equations for m_k , both sides of Eq. (5) were multiplied by a differentiable function $\psi(Y)$ and then were integrated within limits from $-\infty$ to $+\infty$ by Q .

$$\frac{d\left(\int_{-\infty}^{+\infty}\psi(Q)\,p(Q,t)\,dQ\right)}{dt}=\int_{-\infty}^{+\infty}p(Q,t)\,A(Q)\frac{\partial\psi(Q)}{\partial Q}dQ+0.5\int_{-\infty}^{+\infty}p(Q,t)\,B(Q)\frac{\partial^2\psi(Q)}{\partial Q^2}dQ \tag{8}$$

Then, $\psi(Q)$ was replaced with $\psi(Q)=Q^k$, and the Eq. (8) was written as:

$$\frac{dm_k(t)}{dt}=\int_{-\infty}^{+\infty}p(Q,t)\,A(Q)\frac{\partial(Q^k)}{\partial Q}dQ+0.5\int_{-\infty}^{+\infty}p(Q,t)\,B(Q)\frac{\partial^2(Q^k)}{\partial Q^2}dQ\ . \tag{9}$$

For a stationary random process $dm_k(t)/dt=0$, and the drift and diffusion coefficients are constant. Thus, Eq. (9) was simplified as follows:

For k=1:

$$-(\bar{c}-0.5G_{\tilde{c}})m_1-0.5G_{\tilde{c}\tilde{N}}+\bar{N}=0\ . \tag{10}$$

For $k\geq 2$:

$$-k(\bar{c}-0.5kG_{\tilde{c}})m_k+k\bar{N}m_{k-1}-k(k-0.5)G_{\tilde{c}\tilde{N}}m_{k-1}+0.5k(k-1)G_{\tilde{N}}m_{k-2}=0\ . \tag{11}$$

Further, the summands in Eq. (10–11) were divided by $(2\bar{c}+G_{\tilde{c}})$, and new notations were introduced as suggested in (Kovalenko, 1993; Pugachev et al., 1974):

$$a=\frac{G_{\tilde{c}\tilde{N}}+2\bar{N}}{2\bar{c}+G_{\tilde{c}}}\ ;\ b_0=-\frac{G_{\tilde{N}}}{2\bar{c}+G_{\tilde{c}}}\ ;\ b_1=\frac{2G_{\tilde{c}\tilde{N}}}{2\bar{c}+G_{\tilde{c}}}\ ;\ b_2=-\frac{G_{\tilde{c}}}{2\bar{c}+G_{\tilde{c}}}\ .$$

Then, for k = 1, 2, 3, 4 the system of Eq. (10–11) includes:

$$m_1(2b_2+1)-a+b_1=0\ , \tag{12}$$

$$(3b_2+1)m_2+(2b_1-a)m_1+b_0=0\ , \tag{13}$$

$$(4b_2+1)m_3+(3b_1-a)m_2+2b_0m_1=0\ , \tag{14}$$

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$$\left(5b_2+1\right)m_4+\left(4b_1-a\right)m_3+3b_0m_2=0 \ . \tag{15}$$

The set of four moments (m_1, m_2, m_3, m_4) is sufficient to model distributions from the Pearson System (Andreev et al., 2005; Elderton and Johnson, 1969). However, in water engineering we usually use only three-parametric probability distributions fitted to observations (Guidelines, 2004; Guidelines, 1984; Bulletin 17-B, 1982). In this case, the $G_{\tilde{c}} \ll \bar{c}$ is assumed, thus it leads to $b_2=-G_{\tilde{c}}/\left(2\bar{c}+G_{\tilde{c}}\right)\approx 0$ and $\left(4b_2+1\right)\approx 1$, $\left(3b_2+1\right)\approx 1$, $\left(2b_2+1\right)\approx 1$. To model the PDFs (or EPCs) of annual runoff within the Pearson Type III distribution, the system of Eq. (12–15) is simplified as follows:

$$-a+b_1=-m_1 \ , \tag{17}$$

$$b_0+2m_1b_1-am_1=-m_2 \ , \tag{18}$$

$$2m_1b_0+3m_2b_1-am_2=-m_3 \ . \tag{19}$$

Denoting $lk=\begin{pmatrix}-m_1\\-m_2\\-m_3\end{pmatrix}$, $x=\begin{pmatrix}b_1\\b_0\\a\end{pmatrix}$ and $A=\begin{pmatrix}1 & 0 & -1\\2m_1 & 1 & -m_1\\3m_2 & 2m_1 & -m_2\end{pmatrix}$, the parameters a, b_0, b_1 are calculated as $x_i = D_i / D$, where D is the determinant of matrix A, and D_i is the determinant of the matrix obtained by replacing of the column i (1, 2, 3) in matrix A by the vector lk. Finally, the parameters a, b_0, b_1 are calculated as follows:

$$b_1=0.5\left(3m_1m_2-2m_1^3-m_3\right)/\left(m_2-m_1^2\right) \ , \tag{20}$$

$$b_0=0.5\left(m_1^2m_2-2m_2^2+m_1m_3\right)/\left(m_2-m_1^2\right) \ , \tag{21}$$

$$a=0.5\left(5m_1m_2-4m_1^3-m_3\right)/\left(m_2-m_1^2\right) \ . \tag{22}$$

2 Model description

The MARCS model simulates three non-central statistical moments of annual runoff based on a mean annual precipitation for any projected period period of 20-30 years in the future. The projected mean annual precipitation is calculated from global/regional climate models. To perform the model parametrization, historical yearly time series of annual runoff are needed for a period in the past (the reference). Time series of annual runoff are considered to be homogeneous for the reference period, and they are analysed for an absence of trends (Dahmen and Hall, 1990). In this study, a technique of “floating point” (Shevnina et al., 2017) was applied to define the reference period in case study of Iijoki River.

2.1 Model input

To run the MARCS model the historical yearly time series of annual runoff and annual precipitation are needed. Hydrological year books or runoff datasets provide observations from rivers' and streams' gauges, and water runoff is usually expressed in volumetric flow rate (water discharge, m^3s^{-1}). In our study, the volumetric rate was converted to a specific discharge, thus the historical yearly time series of the annual specific discharge (DR, mm $year^{-1}$) were calculated as follows:

$$DR = 1000\ Q\ T / A,$$

where Q is a yearly average water discharge, m^3s^{-1}; T is a number of seconds in a year, and A is the catchment area, m^2. These yearly time series of annual specific discharge are analyzed for homogeneity and trends (Dalmeh and Hall, 1990) to define the reference period (Shevnina at al., 2017). Then, the reference statistical estimators are evaluated as three non-central moments m_k ($m_k = 1/n \sum_{i=1}^{n} DR_i^k$ for k=1, 2, 3) from the time series of annual specific discharge observed in any gauge.

Within the reference period, an annual precipitation is calculated for each year from observations, and these yearly values are expressed in mm $year^{-1}$. Within the projected period, an annual precipitation is calculated for each year from an output of global/regional climate model, and it is expressed in mm $year^{-1}$. The observed and simulated yearly time series are used to estimate the mean annual precipitation for the reference and projected periods correspondingly.

2.2 Model validation

MARCS allows simulation of non-central moments to model a PDF (or EPC) of runoff within the Pearson Type III distribution, *i.e.* provides a probabilistic form of prediction. The end product of the model is the simulated PDF (or EPC), this means that a simulated time series to be compared with observations does not exist. Thus, the simulated PDF (or EPC) is compared to an empirical PDF using statistical tests such as Kolmogorov-Smirnov (Smirnov, 1948). To perform the MARCS model validation and hindcasts, a cross-validation procedure is applied. The idea behind the cross-validation is to divide the whole observational period into two sub-periods with statistically significant differences in mean values (Shevnina et al., 2017).

2.3 Model core

In our study, the core version 0.2 for the probabilistic model MARCS was suggested instead of the version 0.1 shortly described in the annex (Shevnina et al., 2017). The core v0.2 allows evaluation of a skewness parameter for the Pearson Type III distribution. Thus, the formulas include three equations for the parameters a_r, b_{0r}, b_{1r} estimated for a reference period (with low index r):

$$a_r = 0.5 \left(5 m_{1r} m_{2r} - 4 m_{1r}^3 - m_{3r}\right) / \left(m_{2r} - m_{1r}^2\right) , \tag{23}$$

$$b_{0r}=0.5\left(m_{1r}^2 m_{2r}-2m_{2r}^2+m_{1r}m_{3r}\right)/\left(m_{2r}-m_{1r}^2\right) , \quad (24)$$

$$b_{1r}=0.5\left(3m_{1r}m_{2r}-2m_{1r}^3-m_{3r}\right)/\left(m_{2r}-m_{1r}^2\right) . \quad (25)$$

Then, the parameters $\bar{c}_r, G_{\tilde{N}r}, G_{\tilde{c}\tilde{N}r}$ are calculated as follows:

$$\bar{c}_r=\bar{N}_r/\left(a_r-b_{1r}/2\right) , \quad (26)$$

$$G_{\tilde{N}r}=-2b_{0r}\bar{N}_r/\left(a_r-b_{1r}/2\right) , \quad (27)$$

$$G_{\tilde{c}\tilde{N}r}=b_{1r}\bar{N}_r/\left(a_r-b_{1r}/2\right) , \quad (28)$$

where, $\bar{N}_r$ is the mean annual precipitation for the reference period (mm year^{-1}).

For the projected period (see notations with low index *pr*), the parameters $a_{pr}, b_{0\,pr}, b_{1\,pr}$ are calculated from the projected mean annual precipitation ($\bar{N}_{pr}$, mm year^{-1}):

$$a_{pr}=\left(G_{\tilde{c}\tilde{N}pr}+2\bar{N}_{pr}\right)/\left(2\bar{c}_{pr}\right) , \quad (29)$$

$$b_{0\,pr}=-G_{\tilde{N}pr}/\left(2\bar{c}_{pr}\right) , \quad (30)$$

$$b_{1\,pr}=G_{\tilde{c}\tilde{N}pr}/\bar{c}_{pr} , \quad (31)$$

with an assumption that the parameters $\bar{c}, G_{\tilde{N}}, G_{\tilde{c}\tilde{N}}$ are constant for the reference and projected periods (Kovalenko, 1993): $\bar{c}_r=\bar{c}_{pr}, G_{\tilde{N}r}=G_{\tilde{N}pr}, G_{\tilde{c}\tilde{N}r}=G_{\tilde{c}\tilde{N}pr}$. Finally, the projected non-central moments of runoff are calculated as follows:

$$m_{1\,pr}=a_{pr}-b_{1\,pr} , \quad (32)$$

$$m_{2\,pr}=-b_{0\,pr}-2m_{1\,pr}b_{1\,pr}+a_{pr}m_{1\,pr} , \quad (33)$$

$$m_{3\,pr}=-2m_{1\,pr}b_{0\,pr}-3m_{2\,pr}b_{1\,pr}+a_{pr}m_{2\,pr} . \quad (34)$$

2.4 Model output

In our study, the EPCs of annual runoff were modelled within the Pearson Type III distribution commonly used in water engineering (Kountrouvelis and Canavos, 1999; Rogdestvenskiy and Chebotarev, 1974; Matalas and Wallis, 1973). The engineering books suggest evaluating ordinates of runoff EPCs from look-up tables (Guidelines, 1984) depending on a coefficient of variation (CV) and coefficient of skewness (CS), and they are evaluated from non-central moments as follows (Rogdestvenskiy and Chebotarev, 1974):

$$\mathrm{CV}=\sqrt{\left(m_2-m_1^2\right)}/m_1 , \quad (35)$$

$$\mathrm{CS} = \left(m_3 - 3 m_2 m_1 + 2 m_1^3\right) / \mathrm{CV}^3 m_1^3 \quad . \tag{36}$$

These values are calculated from the observations for the reference period, whereas they are simulated by the MARCS model for the projected period. Then, the ordinates of EPC are used to calculate the runoff extremes of required exceedance probability.

3 Model application: a case study

To show how the MARCS model simulates annual runoff values of required exceedance probability for a single catchment, we choose the Iijoki river at Raasakka gauge (Lat 25.411° / Lon 65.335°). The Iijoki river is located north west Finland, and the Raasakka gauge outlines the watershed area of over 14,191 km^2 classified as a catchment of middle size. The catchment has a small population and there are no big hydropower plants to affect the annual runoff, thus we can expect that historical yearly time series of annual runoff do not contain trends connected to artificial regulation. This case study shows an example of set up and output of the probabilistic hydrological model MARCS.

3.1 Model set up: the reference period

The yearly time series of volumetric water discharge of the Iijoki river were extracted from a dataset of the Global Runoff Data Center (GRDC, 56068 Koblenz, Germany). The observations at the Raasakka gauge (ID = 6854600) cover a period 1911–2014 considered as a reference, and do not contain gaps. The reference period was defined as suggested in Shevnina et al. (2017). The annual specific discharge was calculated from the average volumetric water discharge for each year in the reference period. Then, the non-central moments were calculated from the yearly time series of annual specific discharge observed at the Raasakka gauge (Table 1). The reference climatology (the means of precipitation and air temperature) were evaluated from a dataset of NOAA (NOAA/OAR/ESRL PSD, Boulder, Colorado, USA) at a grid node nearest to the watershed centroid (this technique will be discussed in a separate paper as well as methods behind forcing of the MARCS model).

3.2 Model forcing: the projected period

Climate scenarios provide a range of projections for the temperature and moisture regimes in the future. This range is produced by different assumptions behind climate scenarios as well as climate models, however the future projections include simulated time series of precipitation and air temperature. This circumstance opens an opportunity to apply hydrological models to evaluate projections of runoff. In this study, the projections of the Coupled Model Inter-comparison Project 5, CMIP5 (Taylor et al., 2012) for three Representative Concentration Pathways (RCPs) were used to force the MARCS model. For each RCP scenario, the projections of annual precipitation provided by four world-leading global climate models were applied to test the MARCS model's sensitivity to fluctuations in the climate forcing. The mean values of precipitation for the period of 2020–2050 (considered as the projected) were calculated based on the CaESM2 (Chylek et al., 2011), HadGEM2-ES (Collins et al., 2011), INM-CM4 (Volodin et al., 2010) and MPI-ESM-LR (Giorgetta et al., 2013) models (Table 2). The projected means of precipitation $\bar{P}_p$ varied by 2–5 % of the models' averages over the RCP scenarios. However, the means alter substantially between the climate models, especially compared with the reference mean precipitation. Among the climate models considered, the MPI-ESM-LR model projects maximum changes in the mean precipitation compared with the reference period (Tables 1 and 2). The HadGEM2-ES model gives the lowest values for the projected means of precipitation. Generally, the projected means of precipitation slightly vary between the scenarios, but exhibit significant variation between the climate models (the $\bar{P}_{pr}$ range from 619 to 737 mm year^{-1}) for the case of the Iijoki river at Raasaka.

3.3 Model output: projected period

The projected moments of annual runoff of the Iijoki River at Raasakka were simulated for scenarios/models listed in Table 2. The estimates of non-central moments were used to calculate the projected means of annual specific discharge, coefficients of variation (CV) and coefficients of skewness (CS) included to the output of the MARCS model. Table 3 shows the projected means, CVs and CSs simulated from outputs of the HadGEM2-ES and MPI-ESM-LR. These models predict a range for the means of annual precipitation for the projected period. To model the projected EPCs of annual specific discharge of the Iijoki River at Raasaka, the ordinates of the Pearson Type III distribution were extracted from the look-up tables used in hydrological engineering (Druzhinin and Sikan, 2001; Guidelines, 1984), however these values can be estimated from Salvosa (1930). Finally, the projected values of annual discharge of 10 % and 90 % exceedance probabilities were calculated from these ordinates, and the projected values of annual runoff was expressed as volumetric discharge at Raasaka (Table 3).

For the Iijoki River at Raasakka, the means annual specific discharge and CV vary of over 7 % and 5 % correspondingly under the RCP scenarios. However, under RCP85, a maximum for the alteration in the projected means of annual discharge (619 to 737 mm year^{-1}) were obtained, and it could be linked to the decrease or increase in the mean precipitation in the future. Under the projections of the MPI-ESM-LR model, the mean annual discharge increases over 17 % compared to the reference value for RCP85. Generally, it means that water resources in this catchment are expected to increase in term of annual discharge, thus they became available to water users, in particular a hydropower generation potential of the Iijoki river would increase in the future.

For the scenarios/models considered, the projected annual discharges of 10% exceedance probability are increased in the case of the Iijoki River at Raasakka (Table 3), thus the risks connected to energy spills at hydropower stations would expected during the period 2020–2050. At the same time, the risks connected to water shortage are doubted since they are connected to water discharges of 90 % exceedance probability, which are projected to increase. Figure 2 shows another form for the projected EPC of annual runoff for the Kyrönjoki River at Skatila (GRDC ID: 6854900) simulated under three RCP scenarios using the similar set up

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of the MARCS model (will be discussed in a separate paper). The output of the the MARCS model can be served as the EPC of annual discharge (Fig. 2) as well as the projected water discharge of chosen exceedance probabilities (10 %, 90 % in Table 3). To define a range of practical applications of the probabilistic projections of runoff, additional study is needed in close cooperation with water managers and decision makers.

Discussions

The probabilistic hydrological model MARCS uses the AFA approach combining the methods of modelling and frequency analysis. To place the MARCS model among other hydrological models, it is important first to depict its features. The main features of the MARCS model are a direct connection to hydrological engineering practice and effectiveness in terms of computational time. The core v0.2 includes only three parameters to be evaluated from observations, and it produces only three statistical moments of runoff instead of runoff time series. This circumstance makes the computations by the probabilistic model to be effective in terms of time especially compared to physically based conceptual hydrological models. The MARCS model simulates a mean value, coefficient of variation and coefficient of skewness to be further used to model EPC within the Pearson distributions. It produces output as understandable by water engineers familiar with the methods of traditional frequency analysis.

The MARCS model includes six modules (Shevnina and Gaidukova, 2017) and each module allows improvements. In this paper, the new model core v0.2 extending to simulate a third statistical estimator (skewness) was presented. However, the parameters were set as constant for the projected period within the basic parametrization scheme (Kovalenko, 1993). This basic scheme gives over 70–80 % successful hindcasts ("forecasts in the past") for the annual runoff according to the Kolmogorov-Smirnov and Pearson tests (Kovalenko, 1993). A regional oriented parametrization scheme allows improvements in the model efficiency of over 10–13 % (Shevnina, 2011) due to including the projected means of air temperature in the parameters.

In the current version, the hydrological MARCS model is forced by the means of precipitation obtained from global climate models. The spatial resolutions of the global models are coarse, and it makes challenges in simulations of runoff for physically-based hydrological models (Hostetler, 1994) forced by regional climate projections (Xu, 1999). However, the "black box" models seem to be less sensitive to a resolution of climate forcing since their parameters are evaluated "backward". This case study of the Iijoki River at Raasakka shows that the MARCS model gives reasonable changes on the runoff corresponded to the projections from the global climate models. However, the role of the forcing resolution in the modelling uncertainties for the projected mean, CV and CS of annual runoff should be studied further. These uncertainties are now estimated as suggested by Kovalenko (1993). Regional climate models provide good spatial resolution for the climate projections, and this allows study of sensitivity of the MARCS model to the spatial resolution of the climate forcing.

Another question of the MARCS model's forcing is connected to climatological datasets available for the reference and projected periods. The climate models simulate meteorological variables on grids, and node values are interpolated from observations at specific meteorological stations by smoothing over space. In our study, the reference and projected precipitation were evaluated at a

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node of climate model nearest to a catchment centroid, and then these values were considered as representative for the whole catchment. However, the precipitation can also be evaluated on a point corresponded to a meteorological station located within the catchment boundary. It is important to study how the extraction methods for the climate forcing affects the results of the MARCS model.

To place the probabilistic MARCS model among other hydrological models it is also important to outline practical applications. The probabilistic form of a weather prediction serves a good base for decision-making in cost-lost situations (Mylne, 2002; Murphy, 1977, 1976), and the forecasts of river runoff are among others. In this context, the projected exceedance probability curves of multi-year river runoff can be applied in designing of bridges, pipes, dams *etc.* to minimize the future risks connected to extreme floods (Shevnina et al., 2017; Shevnina, 2014; Kovalenko et al., 2014; Kovalenko, 2009) or to water shortage due to droughts (Viktorova and Gromova, 2014). Hydropower energy production depends on water resources. In particular, potential hydropower production are evaluated from mean values of annual runoff (Parkinson and Djilali, 2015; Hamududu and Killingtveit, 2012; Obrezkov, 1988) while the risks in this energy production are connected to extremes: the future runoff may not be enough or too much to support present hydropower facilities. These runoff extremes can be evaluated by the MARCS model based on the AFA approach. It is important to include the needs of decision makers in the projected runoff extremes to define informative forms for the probabilistic projections of multi-year runoff. It can be a topic for further study in close cooperation with water managers and decision makers.

Conclusion

The paper describes the theory and assumptions of the AFA approach as well as the probabilistic hydrological model MARCS (Shevnina and Gaidukova, 2017; Shevnina, 2015). The AFA has been introduced more than 20 years ago and combines the methods of physically-based hydrological modelling and frequency analysis, traditionally applied in water engineering to evaluate the risks connected to infrastructure. The AFA is based specifically on the system for three statistical moments (Pugachev et al., 1974; Rogdestvensky and Saharyk, 1974). The yearly time series of runoff is considered as realization of a random process Markov chain type, and is described by three statistical estimators (moments) used to model an exceedance probability curve of annual runoff within the Pearson Type III distribution. The AFA approach is developed with an assumption of “quasi-stationarity”, which suggests that the extreme runoff in the future differs from the past and can be simulated based on any climate models under any climate scenario.

The probabilistic hydrological model MARCS uses the AFA approach, and allows simulation of the extreme runoff. The features of the model are: the close connection to water engineering due to serving the runoff projection in terms of probability, cheapness computationally and a wide range of techniques allowing model improvement. In this study, the new core v0.2 for the MARCS model was implemented to perform the simulation of the third moment linked to the location parameter of the Pearson Type III distribution (or asymmetry). Generally, it allows improvement in simulations of the runoff extremes since the tailed values of the Pearson Type III distribution are sensitive to fluctuations on the asymmetry (Rogdestvenskiy and Chebotarev, 1974; Matalas and Wallis, 1973). Previously, a ratio CS/CV is assumed to be constant for the reference and projected periods (Shevnina et al., 2017; Kovalenko et al., 2010).

The MARCS model was applied to evaluate the tailed values of 10 % an 90 % of annual runoff from the case of the Iijoki River at Raasakka (Finland) to give an example of the model set up and output. Two forms of the probabilistic runoff projections were presented: the exceedance probability curve and the runoff values of chosen exceedance probability. The practical applications of water management and decision making should be clarified in further studies in close co-operation with water engineers.

Code availability

Currently, the source code for the core v0.2 is distributed under the Creative Commons Attribution 4.0 License and can be downloaded from the link: https://zenodo.org/record/1220096#.WyTXxxxRVhw (Shevnina and Krasikov, 2018), and used freely in a scientific research with reference to this publication. We hope that this type of license provides the best way to create a community of motivated people to further development the model. Then, the source code will be distributed under the terms of a user agreement.

Data availability

The following datasets can be used to set up and forcing the MARCS model: the Global Runoff Data Center (GRDC, 56068 Koblenz, Germany), the NOAA/OAR/ESRL PSD (Boulder, Colorado, USA) as well as the Coupled Model Inter-comparison Project 5, CMIP5 (Taylor et al., 2012).

Sample availability

The sample dataset for the Iijoki River at Raasaka case study is given in https://zenodo.org/record/1220096#.WyTXxxxRVhw (Shevnina and Krasikov, 2018).

Annex: the short user guide the core v0.2, the MARCS model

To set up the model for a single river catchment, the non-central moments should be calculated from historical time series of annual river runoff rate as well as a mean value of annual precipitation rate. These values should be placed manually (lines 45-48 in model_core.py, Shevnina and Krasikov, 2018) as well as the ID number of catchment (line 51, model_core.py). To force the model, the projected mean value of annual precipitation rate should be evaluated from an output of climate model, and then the model_core.py can be running in Unix command line: ./model_core.py XXX (where XXX is the mean of annual precipitation rate for the projected period). The output of the model_core.py in stored in the output file model_GPSCH.txt and include line with following format: the ID of catchment, the first non-central moment estimate of annual runoff rate (mm yr^{-1}) for a reference period, the mean value of annual precipitation rate (mm yr^{-1}) for a reference period, the coefficient of variation for a reference period, the coefficient of skewness for a reference period, the model parameters $\bar{c}$, $G_{\widetilde{N}}$, $G_{\widetilde{c}\,\widetilde{N}}$, the the first non-central moment estimate of annual runoff rate (mm yr^{-1}) for a projected period, the mean value of annual precipitation rate (mm yr^{-1}) for a projected period, the coefficient of variation for a projected period, the coefficient of skewness for a projected period.

Competing interests

The authors declare that they have no conflict of interests.

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Table 1. The MARCS model set up: the Iijoki river at Raasakka as a case study.

GRDC ID	River at Gauge	Length, year	m_{1r}, mm year^{-1}	m_{2r}, mm^2 year^{-1}	m_{3r}, mm^3 year^{-1}	$\bar{N}_r$, mm year^{-1}	$\bar{T}_r$ *, °C
6854600	Iijoki at Raasakka (Finland)	100	379	149343	60811610	625	0.2

Notes: m_{1r}, m_{2r}, m_{3r} are the moments of runoff as well as the mean of precipitation ($\bar{N}_r$) were evaluated from observations. The mean air temperature ($\bar{T}_r$)* was not used in the model set up in case of the Iijoki river, however this value allows advancement of the model parametrization (Shevnina et al., 2017).

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Table 2. The forcing of the MARCS model for the case study of the Iijoki river at Raasakka.

Global climate model	Climate scenario					
	RCP26		RCP45		RCP85	
	$\bar{T}_{pr}$, °C*	$\bar{P}_{pr}$, mm year^{-1}	$\bar{T}_{pr}$, °C	$\bar{P}_{pr}$, mm year^{-1}	$\bar{T}_{pr}$, °C	$\bar{P}_{pr}$, mm year^{-1}
CaESM2	2.9	673	2.7	652	2.7	652
HadGEM2-ES	1.4	635	2.6	637	2.2	619
INM-CM4	–	–	1.3	645	1.4	660
MPI-ESM-LR	2.5	704	2.2	695	2.9	737

Notes: Projected mean of air temperature ($\bar{T}_{pr}$)* is needed for a regional parametrization scheme (see details Shevnina, 2011), and these values were not used in the model forcing in the case of the Iijoki river at Raasakka. $\bar{P}_{pr}$ is the projected mean of annual precipitation amount.

Table 3. The projected climatology and statistics of annual runoff: a case of the Iijoki river.

Value	Reference period: 1914–2014	Projected period: 2020–2050					
		HadGEM2-ES			MPI-ESM-LR		
		RCP85	RCP45	RCP26	RCP85	RCP45	RCP26
PRE, mm year^{-1}	625	619	637	635	737	695	704
DR, mm year^{-1}	380	375	386	385	447	421	427
CV	0.19	0.2	0.19	0.19	0.16	0.17	0.17
CS	–0.04	–0.04	–0.04	–0.04	–0.04	–0.04	–0.04
$Q_{10\%}$, m^{3}s^{-1}	475	473	483	481	527	505	512
$Q_{90\%}$, m^{3}s^{-1}	293	278	297	296	331	354	359

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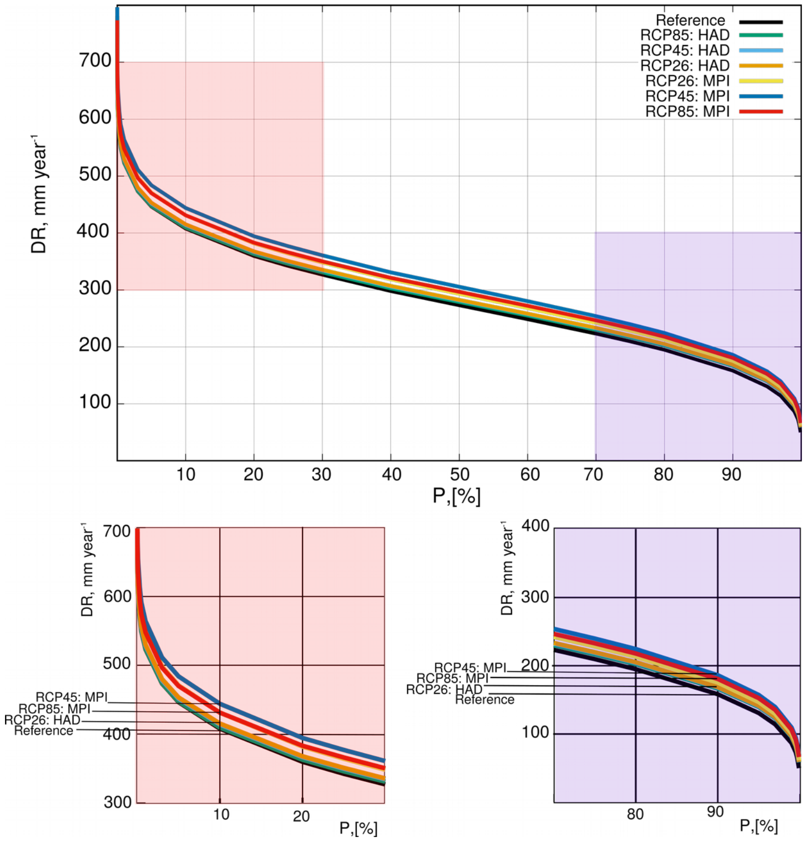

Figure 1: The variability on tails of the EPCs of annual runoff for the reference (black) and projected (colours) periods.