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# PROBABILISTIC PROJECTIONS OF ANNUAL RUNOFF AND HYDROPOWER PRODUCTION IN FINLAND

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**Introduction.** Humans use water to produce energy for a long history. Water managers use hydrological forecasts to improve a decision-making in water-depending economics, and a hydropower industry is among others. A basic idea behind the decision-making is to optimize resources (i.e. water) in a production of a monetary value (i.e. energy generation). The decision-making is always connected to an assessment of risks. The hydropower industry is sensitive to amount of water resources available for energy production, and the risks are connected to extreme runoff events: energy spills due to over flooding or interruptions in plants' operation due to water shortages. Water engineering defines the runoff extremes as values with probabilities, which are estimated from tails of exceedance probability curves (EPCs) of river runoff. The probability indicates a likelihood that a particular runoff value will be exceeded. This study aims to evaluate a potential hydropower production in term of probability based on a long term projection for extremes in annual runoff. To achieve this aim, the EPCs of annual runoff rate (ARR) were simulated from mean values of annual precipitation amount available from climate projections. In our study, an Advance of Frequency Analysis (AFA) method resulted on a probabilistic hydrological model MARrkov Chain System (MARCS) was applied. The AFA 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 (Kovalenko, 1993). The MARCS model allows simulation of non-central moments of runoff (Shevnina and Gaidukova, 2017; Shevnina, 2015).

$$\boxed{m_{n-1} b_0 n + m_n [b_1(n+1) - a] + m_{n+1}[(n+2) b_2 + 1] = 0}$$

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

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

$$\begin{aligned} &m_1(2b_2+1) - a + b_1 = 0 \\ &(3b_2+1) m_2 + (2b_1 - a) m_1 + b_0 = 0 \\ &(4b_2+1) m_3 + (3b_1 - a) m_2 + 2b_0 m_1 = 0 \\ &(5b_2+1) m_4 + (4b_1 - a) m_3 + 3b_0 m_2 = 0 \end{aligned}$$

$$\boxed{\bar{c}_r = \bar{c}_{pr}, G_{\tilde{N}r} = G_{\tilde{N}pr}, G_{\tilde{c}\tilde{N}r} = G_{\tilde{c}\tilde{N}pr}}$$

$$G_{\tilde{c}} << \bar{c} \qquad b_2 = -G_{\tilde{c}}/(2\bar{c} + G_{\tilde{c}}) \approx 0 \quad (4b_2+1) \approx 1 \quad (2b_2+1) \approx 1$$

$$\begin{aligned} -a + b_1 &= -m_1 \\ b_0 + 2m_1 b_1 - a m_1 &= -m_2 \\ 2m_1 b_0 + 3m_2 b_1 - a m_2 &= -m_3 \end{aligned}$$

$$\begin{aligned} &m_1 \implies Norm,\ \bar{Q} = m_1 \\ &m_1,\ m_2 \implies Coefficient\ of\ variation,\ CV = \sqrt{(m_2 - m_1^2)}/m_1 \\ &m_1, m_2, m_3 \implies Coefficient\ of\ skewness,\ CS = (m_3 - 3m_2 m_1 + 2m_1^3)/(CV^3 m_1^3) \end{aligned}$$

$$\begin{aligned} \bar{c}_r &= \bar{N}_r/(a_r - b_{1r}/2) \\ G_{\tilde{N}r} &= -2b_{0r}\bar{N}_r/(a_r - b_{1r}/2) \\ G_{\tilde{c}\tilde{N}r} &= b_{1r}\bar{N}_r/(a_r - b_{1r}/2) \end{aligned} \qquad \begin{aligned} m_k &= 1/n \sum_{i=1}^{n} Q_i^k \\ \bar{N} &= 1/n \sum_{1}^{n} PRE \end{aligned}$$

Fig. 1. The probabilistic hydrological model MARCS: theoretical basis.

**Method.** In our study, the MARCS model simulated three non-central statistical moments of annual runoff rate (Fig.1) for a projected period (2020-2050). These moments were used to calculate the mean value, coefficient of variation and coefficient of skewness, and then to evaluate the runoff with percentiles of exceedance probability for 10 % and 90 %. The projected EPCs were modeled within the Pearson Type 3 distribution.

To set up the model, three non-central moments were estimated from the observed runoff time series for a reference period (1960-1990). To force the model the mean values of annual precipitation rate were evaluated from six climate projections providing by two climate models under three climate scenarios. This set of the projected climatology provided range of changes in an annual precipitation for each river basin considered. Thus, the model output consisted of a set of projected mean value, coefficient of variation and coefficient of skewness as well as the EPCs.

The potential hydropower production (PHP) was calculated depending on annual runoff (Parkinson and Djilali, 2015; Hamududu and Killingtveit, 2012) in an assumption that a specifics of hydropower network facilities will not changed over the projected period. Thus, the changes of the PHP (dPHP,%) in the future was considered to be only related to the changes in annual runoff rate.

**Data.** The historical time series of river discharges were extracted from the Global Runoff Data Center (GRDC, 56068 Koblenz, Germany) for 12 gauging sites located in Finland (Table 1). The time series of annual runoff rate were analysed for a homogeneity (Dahmen and Hall, 1990). The homogenizes time series of annual runoff were used to evaluate three non-central statistical moments for a reference period.

The yearly time series of annual precipitation rate (mm yr-1) were extracted from the UDel_AirT_Precip dataset provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (Fig. 2, a). The dataset of the Coupled Model Inter-comparison Project 5, CMIP5 (Taylor et al., 2012) were used to force the MARCS model. The forcing was evaluated from the outputs of two climate models HadGEM2-ES (Collins et al., 2011) and MPI-ES-LR (Giorgetta et al., 2013) under and three Representative Concentration Pathways (RCP26, RCP45 and RCP85) scenarios (Fig. 2,b).

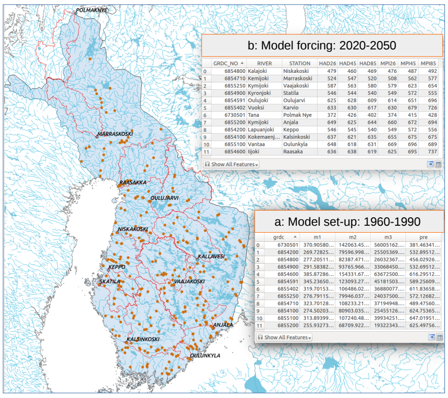


Fig. 2. The catchments (red lines), hydropower plants (dot).

Table 1. The gauging sites considered in this study.

| GRCD ID | River | Station | Area, $km^2$ | Altitude, m asl | Start | End | Length, yr |
|---|---|---|---|---|---|---|---|
| 6730501 | Tana | Polmaknye | 14160 | 20 | 1911 | 2007 | 97 |
| 6854100 | Kokemaenjoki | Kalsinkoski | 26025 | 30 | 1931 | 1992 | 62 |
| 6854200 | Lapuanjoki | Keppo | 3949 | 23 | 1931 | 2012 | 82 |
| 6854591 | Oulujoki | Oulujarvi | 19839 | 121 | 1950 | 2013 | 64 |
| 6854600 | Iijoki | Raasakka | 14191 | 19 | 1911 | 2013 | 103 |
| 6854710 | Kemijoki | Marraskoski | 12303 | 93 | 1971 | 2013 | 43 |
| 6854800 | Kalajoki | Niskakoski | 3065 | 30 | 1911 | 2011 | 101 |
| 6854900 | Kyronjoki | Skatila | 4833 | 5 | 1911 | 2012 | 102 |
| 6855100 | Vantaa | Oulunkyla | 1680 | 7 | 1937 | 2013 | 77 |
| 6855200 | Kymijoki | Anjala | 36275 | 24 | 1938 | 2013 | 76 |
| 6855250 | Kymijoki | Vaajakoski | 17684 | 84 | 1941 | 2013 | 73 |
| 6855402 | Vuoksi | Kallavesi | 1627 | 84 | 1931 | 2012 | 82 |

$$Q_p = k_p \frac{ARR\ Area}{T}$$

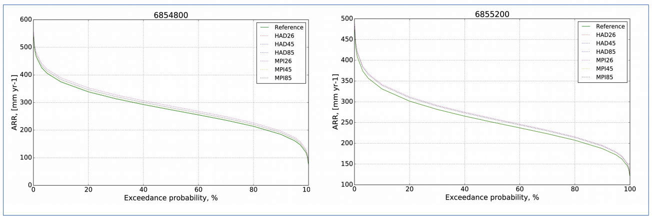


Fig. 3. The simulated EPCs (dotted lines) and the reference EPC (line) of ARR.

Table 2. The projected annual runoff rate values together with their exceedance probabilities: the case of Kyronjoki at Skatila.

| Scenario/ Model | Exceedance probability, % | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 99.9 | 99.7 | 99.5 | 99 | 97 | 95 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | 5 | 3 | 1 | 0.5 | 0.3 | 0.1 |
| Reference | 99.3 | 111 | 117 | 127 | 148 | 161 | 182 | 211 | 235 | 257 | 280 | 304 | 331 | 365 | 416 | 463 | 495 | 560 | 599 | 626 | 684 |
| HAD26 | 102 | 114 | 121 | 131 | 153 | 165 | 187 | 217 | 241 | 264 | 287 | 311 | 338 | 373 | 425 | 472 | 504 | 570 | 609 | 637 | 695 |
| HAD45 | 102 | 114 | 120 | 131 | 152 | 165 | 186 | 216 | 241 | 263 | 286 | 310 | 337 | 372 | 424 | 471 | 503 | 568 | 607 | 635 | 693 |
| HAD85 | 101 | 113 | 119 | 129 | 151 | 163 | 185 | 215 | 239 | 261 | 283 | 307 | 335 | 369 | 421 | 468 | 500 | 565 | 604 | 632 | 690 |
| MPI85 | 104 | 116 | 123 | 134 | 156 | 169 | 191 | 221 | 246 | 268 | 291 | 316 | 343 | 378 | 431 | 478 | 511 | 577 | 616 | 644 | 702 |
| MPI45 | 108 | 121 | 128 | 139 | 161 | 175 | 197 | 228 | 253 | 277 | 300 | 325 | 353 | 388 | 442 | 490 | 523 | 589 | 629 | 657 | 716 |
| MPI26 | 103 | 115 | 122 | 132 | 154 | 166 | 188 | 218 | 243 | 265 | 288 | 312 | 340 | 375 | 427 | 474 | 507 | 572 | 611 | 639 | 697 |

**Results.** The projected means of annual precipitation rate ($dPRE_{2050}$) were used forced the MARCS model (Fig.2,b). The outputs of two climate models under three scenarios provided the changes in precipitation ranged from 2.0 to 12.0 %, with an average of 5.0%. The largest increase on precipitation was proposed by MPI-ES-LR whereas the smallest values of $dPRE_{2050}$ were suggested by HadGEM2-ES, and both cases were obtained under the RCP85. Generally, the $dPRE_{2050}$ were increase from South to North of Finland, with the maximums revealed for the catchments located in Lapland, Oulu and Savu-Karelia regions.

Figure 3 shows two examples of the projected EPCs, and Table 2 gives an example of the ARR values within the range of exceedance probability percentiles for all climate scenarios/models considered. It should be noticed, that the changes in the ARR's tailed values (extreme runoff) differ from the changes in the mean values of runoff.

To evaluate the changes in potential hydropower production (dPHP) in term of exceedance probability, we use the projected changes in ARR values with percentiles 10% and 90% (Fig. 4 left and right boxes). The results show, that the dPHP with percentile 10% are expected to increase for more than 15 % for the catchments located in the North of Finland. In this region, we suggest to consider to reconstruct hydropower facilities since the risks of energy spills on hydropower plants may increase.

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**Discussions and conclusion.** Numerous studies of climate related effect on hydropower industry are mostly addressed to changes only on means of annual runoff (Parkinson and Djilali, 2015; Hamududu and Killingtveit, 2012). Thus we cannot compare our results for the projected PHP with 10% / 90% exceedance probability with others. However, our estimation for the mean PHP suggests to increase of hydropower resources in Finland for 5–25 %, which is in accordance to basin-by-basin estimations given by Veijalainen et al., (2012). In our study, only relative changes of the PHP were considered in assumption that hydropower generation facilities will not change during the projected period. However, it is also possible to include specific plant details such as hydraulic head and turbine efficiency, and calculate future exceedance probability for potential hydropower production in absolute values. This is a topic of a further study.

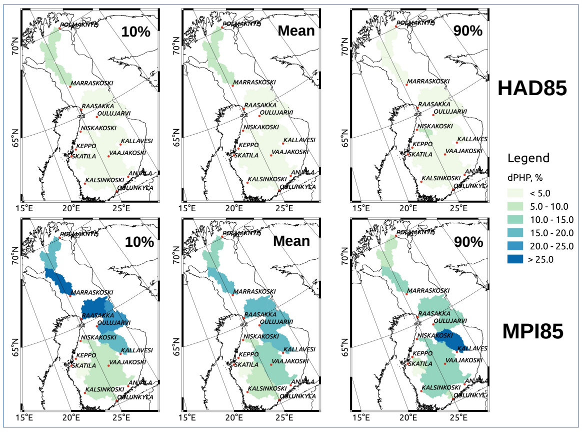


Fig. 4. The changes in the potential hydropower production in term of percentiles.

**References**: *Dahmen and Hall, 1990*: Screening of hydrological data: tests for stationarity and relative consistency. *Parkinson and Djilali, 2015*: Robust response to hydro-climatic change in electricity generation planning. *Hamududu and Killingtveit, 2012*: Assessing of Climate Change Impacts on Global Hydropower. *Veijalainenet al., 2012*: Modeling and statistical analysis of catchment water balance and discharge in Finland in 1951–2099 using transient climate scenarios. *Taylor et al., 2012*: An overview of CMIP5 and the experiment design. *Collins et al., 2011*: Development and evaluation of an Earth-system model – HadGEM2. *Giorgetta et al., 2013*: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the CIMIP5. *Kovalenko, 1993*: Modeling of hydrological processes. *Shevnina, 2015*: Long term probabilistic projections of maximal runoff on the territory of the Russian Arctic.