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Long-term river runoff in South West Africa: scenario-based assessment of persistent changes

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ABSTRACT

The technique of assessing the hydrological impacts of climate change is considered in article. Probability characteristics of river runoff in South West Africa were estimated on different climate scenarios. Anomalous zones on norms and coefficients of variation of annual runoff were identified. In these zones the most probable faults in operation of hydrotechnical structures will expect.

Keywords: Annual runoff, Probabilistic characteristics, Climate scenarios, Africa

Abbreviations: RSHU – Russian State Hydrometeorological University; FPK – equation Fokker–Planck–Kolmogorov; IPCC – Intergovernmental Panel on Climate Change

INTRODUCTION

Economic activities across the river catchments and climate variations of anthropogenic and natural origin lead to changes in probability characteristics within the long-term runoff patterns. Assessments of such changes in hydrological regime were attempted by international science but those considered only the long-term norms of river runoff (Steynor A., 2009). A method of scenario assessments for the higher-order moments of probability distributions was developed in RSHU; however, its application for African conditions has been problematic until recently. The reason lies in instability of statistical moments under conditions of high air temperature, which cause increased evaporation. This leads to uncertainty in scenario-based estimates for probable water flows. Stability to the moments is brought by involving additional phase variables; their number is determined by the fractal diagnostics. However, their selection from multivariate distributions is a very time-consuming task and its solution is not yet finalized for a wide-scale practical application. Successful finding in this area refers to conditional probability density distribution of water flow, assuming that the second variable, i.e., evaporation, is fixed at the normal level (Kovalenko V. et al, 2008).

With view of physiographic conditions in the African continent, the most appropriate direction (in terms of the mainstream engineering calculations) lies in simplifying the runoff model instead of making it more complex. This can be reached by adapting the model to the insufficiently studied long-term runoff regime, against unstable higher-order moments. Such approach was first used by Dr. Abdellatif Hamlili from Algeria (Kovalenko V. et al, 2010).

Thus, the African hydrologists got tools to perform a stable scenario-based assessment of long-term runoff characteristics. This enabled solution to this problem both in the North and South West Africa, with its rather dense river network (not relevant to the East Africa, due to the lack of a dense river network and sampling stations at rivers).

The objective of this paper is to demonstrate the application of the above method in assessing probability characteristics of the long-term runoff in South Africa by the mid-XXI century, for the most probable climate scenarios.

Motivation for the present research is as follows. Until recently, long-term runoff regime in South West Africa (and Africa, in general) has been estimated mainly upon the Digital Atlas of the World Water Balance (Atlas…, 1974). Presented maps of the long-term annual runoff and runoff coefficients are based on the assumption of statistical stationarity of hydrological series and stability of the initial moments of probability distributions.

The observed phenomenon of global warming (confirmed by instrumental measurements) gives rise to suggestion about the failure of stationarity condition and the need of methods to assess long-term changes in projected hydrological characteristics. Such method (more precisely, the methodology) based on the FPK model was extensively developed for the evolution of water flow probability density in RSHU. However, applying this methodology for the situation in Africa (as well as the southern regions of the Russian Federation) did not provide the expected results. The reason was that under a single-phase (runoff) description of hydrometeorological processes in watersheds, higher-order moments of probability distributions become unstable. This instability is of physical nature and does not arise directly from the insufficient length of observation series, which is typical for the African continent (Kovalenko V., 2010).

To overcome this instability, the so-called partial infinite modeling and forecasting (Kovalenko V. et al, 2006) was developed in RSHU. Its main point is that the “unstable task is immersed” in the extended phase space. Along with the runoff characteristics, it includes other hydrometeorological elements, such as evaporation. The limits of this extension are determined by the fractal diagnostics methods, which were tested by Dr. Kouassi Armand for Africa (Kovalenko V. et al, 2008; Kouassi A., 2007). At present, the practical application of multivariate probability distribution is hampered by several reasons. Therefore, an alternative way to cope with instability lies in simplifying the models through reducing the influence of multiplicative noise, as Dr. Hamlili Abdellatif demonstrated successfully for the North West Africa (Kovalenko V. et al, 2010). However, a huge southwestern African region was not covered in the previous scenario-based assessments of hydrological consequences from climate change. Our paper is aimed to fill this gap.

MATERIALS AND METHODS

Our methodology for assessing long-term changes in the annual runoff is based on a system of differential equations for the initial moments, which approximates the FPK equation (Kovalenko V. et al, 2006):

$$\begin{aligned}
dm_1/dt &= -(\bar{c} - 0{,}5\, G_{\tilde{c}})m_1 + \bar{N} - 0{,}5\, G_{\tilde{c}\tilde{N}};\\
dm_2/dt &= -2\,(\bar{c} - G_{\tilde{c}})m_2 + 2\bar{N}m_1 - 3\, G_{\tilde{c}\tilde{N}} m_1 + G_{\tilde{N}};\\
dm_3/dt &= -3\,(\bar{c} - 1{,}5\, G_{\tilde{c}})m_3 + 3\bar{N}m_2 - 7{,}5\, G_{\tilde{c}\tilde{N}} m_2 + 3G_{\tilde{N}} m_1;\\
dm_4/dt &= -4\,(\bar{c} - 2\, G_{\tilde{c}})m_4 + 4\bar{N}m_3 - 4\cdot 3{,}5\, G_{\tilde{c}\tilde{N}} m_3 + 6G_{\tilde{N}} m_2,
\end{aligned} \qquad (1)$$

where m_i ($i = \overline{1,4}$) are initial statistical moments; $c = 1/k\tau = \bar{c} + \tilde{c}$ (here k – runoff coefficient; τ – relaxation time of the river basin; $\bar{c}$ – expectation; $\tilde{c}$ – white noise); $N = \dot{X}/\tau = \bar{N} + \tilde{N}$ (here $\dot{X}$ – precipitation intensity; $\bar{N}$ – expectation; $\tilde{N}$ – white noise); $G_{\tilde{c}}$, $G_{\tilde{N}}$ – intensity, and $G_{\tilde{c}\tilde{N}}$ – mutual noise intensity.

Since the existing climate scenarios are inherently balanced, we can assume that $dm_i/dt = 0$ ($i = \overline{1,4}$) and restrict further to the algebraic system. Thus, the scenario assessments are graded (by steps of 20–30 years, which are presented in climate scenarios, as well). Another important simplification is neglecting m_4 moment, since its reliable statistical estimate requires long observation series, which are unavailable for South West Africa. For the same reason, we can omit the m_3 projection and retain in the new climate model a fixed ratio between the coefficients of skewness and variation corresponding to the current climate.

Thus, the system (1) is reduced to two algebraic equations (The methodical recommendations..., 2010):

$$\begin{aligned}
m_1 &= \bar{N}/\bar{c};\\
m_2 &= (G_{\tilde{N}} + 2\bar{N}m_1)/2\bar{c},
\end{aligned} \qquad (2)$$

which is parameterized by only two constants ($\bar{c}$ and $G_{\tilde{N}}$). Under modern developments in hydrometeorological research, $\bar{c}$ parameter could be "revived" in the new climate model by linking it with the air temperature and empirical precipitation formulas.

In this study we used the open-source climate scenarios: Commit, SRA1B, SRA2, and SRB1 (The IPCC…, 2009). Climate information is provided there as normal values of air temperature and precipitation for certain periods. We selected the time frame from 2040 to 2069. Scenario norms of meteorological characteristics are linked to geographic grid nodes, in increments of 2.5 degrees in latitude and longitude.

Selected climate scenarios differ from each other by the following features. The Commit (so-called "ideal") scenario implies that the rate of greenhouse gas emission remains at the level of year 2000. The SRA1B scenario describes a very rapid economic development and population growth; the maximum is reached in mid-XXI century and declines thereafter, due to the development of novel efficient technologies using alternative energy sources. The SRA2 scenario assumes a continuous global-wide population growth and economic development of certain countries, thus leading to slow development in new technologies. The SRB1 scenario is similar to the SRA1B scenario and is distinguished by an assumption of the more rapid economic development and population growth. If applied to South Africa, these scenarios suggest that by 2070 precipitation will decrease by 3–12 % and the temperature will rise by 1.0–2.9 °C, depending on the selected scenario.

To build the information and technology database and implement adaptation of the methodology of scenario-based assessments of hydrological consequences from climate change to South Africa conditions, we used 114 annual runoff series and included West Africa. These series were processed with the entire set of current analytical methods (validating uniformity of time series, the presence of high-water and low-water phases, etc.), in order to ensure their applicability in evaluating the calculated hydrological characteristics to be mapped. The table 1 below provides information about the most typical series and calculated meteorological characteristics.

Based on to data presented in the table and data for West Africa and using the standard GIS software (*ArcView*, *Surfer*), we built distribution maps for the calculated characteristics, as demonstrated by the examples in Fig. 1.

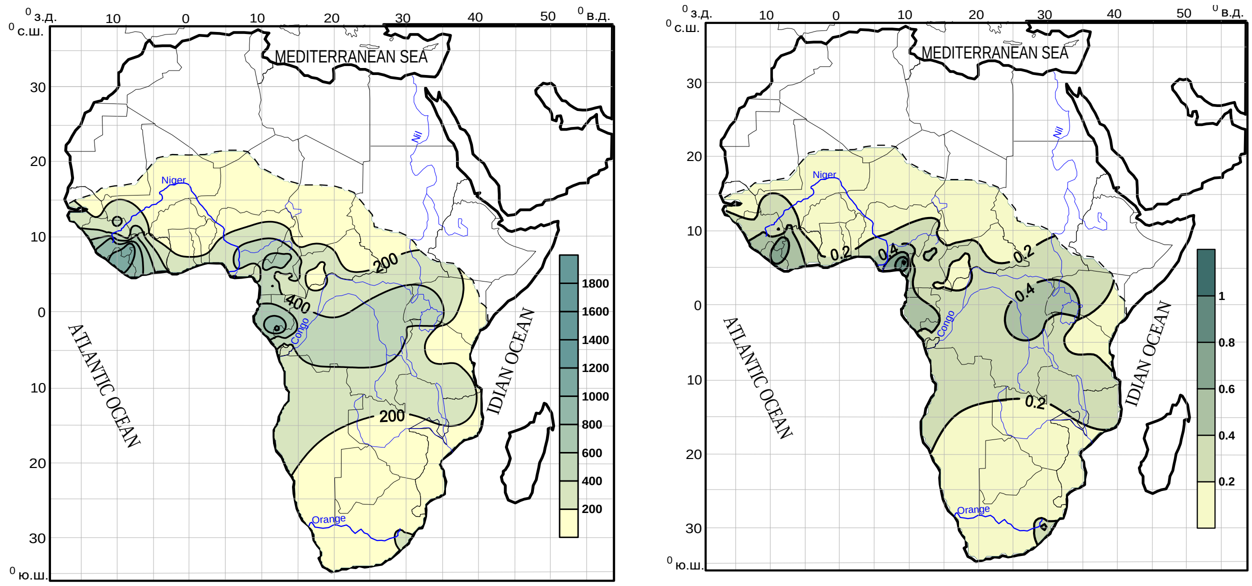
These maps (distribution map for *Cv* was built for the first time) enable calculations of water flow probability needed for secure operation of existing and projected hydraulic structures. Moreover, these maps allow grid parameterization of the model and create interfaces for hydrological and meteorological domains.

Table 1

Calculated hydrometeorological characteristics

River – Station	F (km²)	h (mm)	Cv	Cs	$r(1)$	k	$G_{\tilde{N}}$
MATLABAS – HAARLEM EAST	1054	34	0.80	1.81	0.07	0.06	26
MEGALIES – SCHEERPOORT	1171	26	1.02	2.17	0.34	0.04	45
BOESMANS – DONKER HOEK ALICEDALE	1479	8	1.41	2.31	-0.24	0.01	35
MOOIRIVIER – DOORNKLOOF	1546	182	0.50	1.27	0.32	0.21	187
MKOMAZI – CAMDEN	1744	387	0.44	1.13	0.18	0.51	352
WONDERBOOM SPRUIT – DIEPKLOOF	2397	19	1.25	2.90	-0.14	0.04	181
KEISKAMMA –FARM	2530	40	0.63	1.37	-0.08	0.07	107
OLIFANTS – WOLWEKRANS	3256	51	0.73	2.03	0.21	0.09	344
KLIP – DELANGESDRIFT	4152	48	0.95	2.99	0.44	0.07	1097
INCOMATI – HOOGGENOEG	5540	77	0.51	0.91	0.14	0.12	786
BUFFELSRIVIER – TAYSIDE	5887	121	1.57	5.72	0.13	0.15	16350
SANDRIVIER – ZAMENKOMST	6731	16	1.01	2.59	0.19	0.04	103
DORING – ELANDS DRIFT - ASPOORT	6895	39	0.62	1.03	0.10	0.13	410
GROOT-VIS – BRANDT LEGTE PIGGOT'S BRIDGE	23067	8	1.49	4.20	0.02	0.02	8576
TUGELA – MANDINI	28920	105	0.49	0.49	0.21	0.13	34333
GROOT-VIS – MATOLEMA'S LOCATION OUTSPAN	29745	10	0.51	0.62	0.00	0.02	1906
ORANGE – ALIWAL NOORD	37070	118	0.57	1.35	0.09	0.16	76778
VAAL – ELANDSFONTEIN ENGELBRECHTSDRIFT	38564	36	0.81	1.96	0.25	0.05	48420
KWE KWE – CACTUS POORT DAM	1217	44	1.05	1.64	0.34	0.07	94
KWE KWE – CACTUS POORT DAM	1250	84	3.25	5.68	-0.01	0.13	1811
SEBAKWE – SEBAKWE DAM	1622	115	0.96	1.03	0.41	0.16	409
INGESI – BELINGWE ROAD	1680	57	1.01	1.32	0.30	0.09	221
INSIZA – FILABUSI UPPER WEIR	2000	36	1.29	3.30	0.20	0.06	266
ODZI – ODZI BRIDGE CONTROL SECTION	2498	132	0.47	0.30	0.24	0.13	362
UMZINGWANI – GLASS BLOCK	2504	48	1.20	2.23	0.04	0.08	506
MUNYATI – DYKE	2662	80	0.88	0.95	0.38	0.09	776
MACHEKE – CONDO	3383	132	0.65	0.50	0.06	0.15	1111
SEBAKWE – DUTCHMAN'S POOL DAM	4170	77	1.00	1.55	0.34	0.11	1836
UMFULI – TWYFORD WEIR	5180	78	1.00	1.49	0.13	0.10	3353
UMNIATI – POWER STATION WEIR	5890	58	0.86	1.37	0.19	0.07	2522
SAVE – CONDO	11174	116	0.72	0.76	-0.07	0.14	12715
GWAAI – KAMATIVI	38600	17	0.81	3.11	0.18	0.03	21796

Notations: F – catchment area; h – runoff depth; Cv – coefficient of variation; Cs – coefficient of skewness; $r(1)$ – coefficient of autocorrelation; k – coefficient of runoff; $G_{\tilde{N}}$ – intensity of the external noise.



a) *b*)

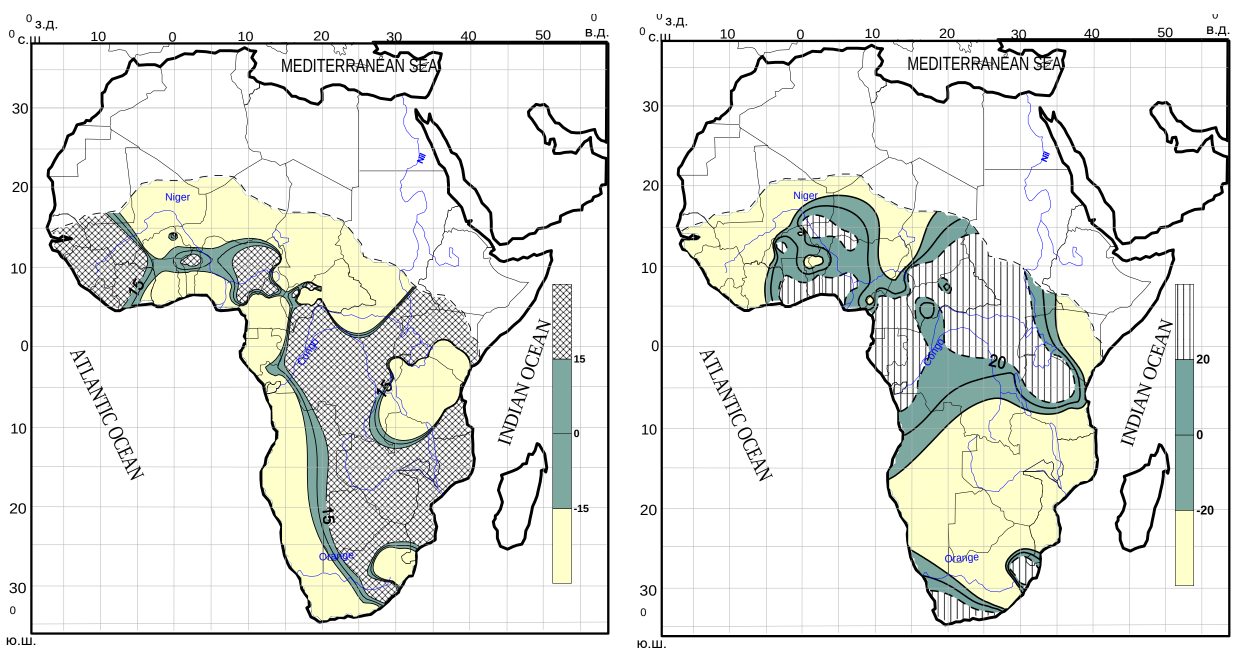
Figure 1

Distribution of the normal runoff depth *h* (*a*) and coefficient of variation *Cv* (*b*) across the South West Africa, calculated upon the actual runoff series

RESULTS AND DISCUSSION

Based on the data obtained from these maps and the above-mentioned climate scenarios, we performed a scenario-based assessment of calculated hydrological characteristics. For each prediction scenario, the projected and actual maps were compared (presented in Fig. 1) and the zones with significant deviations (an example for the Commit scenario is shown in Fig. 2).

The maps developed under this research offer wide opportunities in sensitivity assessment of water-dependent economic sectors in South and West Africa (hydraulic engineering, irrigation, hydropower, etc.) to possible climate changes. The method presented in this paper is independent, as such, either of warming or cooling. Its essential prerequisite is the availability of scenario with data on the expected air temperature and precipitation.



a) *b*)

Figure 2

Statistically significant deviations between the predicted (2040-2069) and actual norms (*a*) and coefficients of variation (*b*)

CONCLUSION

A method for scenario-based assessment of long-term changes in the hydrological regime of South Africa is proposed and tested on both actual and scenary materials. This method builds upon the common methodology developed in Russia and used in the relevant estimates. Its application was adapted to physiographic conditions of South Africa and first presented in this paper. Geographical maps of distribution of the actual runoff characteristics and their predicted deviations allows us to provide a security assessment of the existing and projected hydraulic facilities, in terms of the present and future hydrological regime.

SUMMARY OF RESEARCH

1. Method for the assessment of the probability characteristics, developed in Russia, was approved for the conditions of the African continent.
2. Forecasts of norms and coefficients of variation of annual runoff for the 114 watersheds in South West Africa were made on climatic scenarios Commit, SRA1B, SRA2, SRB1. Revealed, that the falls in the norms of annual runoff in rivers Orange, Limpopo, Congo will expect to 2070 year. A significant change in the coefficient of variation is predicted in South and Central Africa.
3. Zones with the forecast hydrological characteristics significantly differed from the actual were revealed. These areas include the Limpopo river basins, the Congo, the upper reaches of the Niger, they can expect a threat to the normal operation of hydrotechnical structures.

FUTURE ISSUES

The planning and operation of hydrotechnical structures must take into account the future climatic conditions. Techniques, discussed in this article, offer the option of taking into account the climate in engineering calculations. Future research in this area will be associated with the use of a new climate scenarios, that will take into account not only the norm of meteorological parameters, but also other of their probability characteristics.

DISCLOSURE STATEMENT

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Conflict of interest

The authors declare that there is no conflict of interest.

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Data and materials availability

All data associated with this study are present in the paper.

Peer-review

External peer-review was done through double-blind method.

REFERENCE

1. Atlas of World Water Balance. Gidrometeoizdat, 1974, 46 maps.
2. Kouassi A.B.G. Fractal diagnostics annual runoff in West Africa / Investigated in Russia, http://zhurnal.ape.relarn.ru/articles/2007/079.pdf.
3. Kovalenko V. V. The hydrological reliability of hydraulic structures for unsteady climate / Hydraulic building, 2010, 4, 41–44.
4. Kovalenko V. V., Gaidukova E. V., Chistyakov D. V., Hamlili A. Prognostic models of development of processes

of catastrophic long-term annual river runoff formation / Russian Meteorology and Hydrology, 2010, 10, 64–70.

5. Kovalenko V.V., Gaidukova E.V., Kuassi A. B. G. Forecasting the changes in fractal dimension of the long-term river runoff / Geography and natural resources, 2008, 4, 136–143.
6. Kovalenko V.V., Viktorova N. V., Gaidukova E. V. Modeling of hydrological processes. Textbook. St. Petersburg, RSHU Publishers, 2006, 559.
7. Steynor A.C., Hewitson B. C., Tadross M. Projected future runoff of the Breede River under climate change // Water SA Manuscript, 2009/07/30.
8. The IPCC Assessment Reports / IPCC, 2009. – http://www.ipcc.ch
9. The methodical recommendations according to the supplied charges of projected hydraulic engineering structures at the unsteady climate / Under edition V.V. Kovalenko. St. Petersburg, RSHU Publishers, 2010, 50.