Assessment of applicability of MIKE 11-NAM hydrological module for rainfall runoff modelling in a poorly studied river basin

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ABSTRACT

Introduction. The need to simulate hydrological processes is caused by, among other factors, the complexity of hydrological systems and data insufficiency due to the unavailability or a small number of instrumental observations. Recently, the reanalysis of the climate data supplied by the world’s leading meteorological centres has been used quite successfully in the regions that suffer from the deficit of instrumental information. This paper assesses the applicability of climate reanalysis data to rainfall runoff (“rainfall runoff”) modelling in the poorly studied river basin in Eritrea.

Materials and methods. Climate Forecast System Reanalysis (CFSR) data generated by the National Centre for Environmental Prediction (USA) were used. Besides, high-resolution topographic information, generated by the SRTM international research project, was also applied to set the drainage area boundaries and to simulate the river network using such tools as MIKE and GIS. In addition, calibration and validation (evaluation) of the hydrological model (simulation quality) were performed using the Nash-Sutcliffe efficiency criterion, the determination coefficient, and the root mean square error of volumetric and peak flow rates.

Results. The results suggest that a considerable overestimation of precipitation in the reanalysis data set, which in turn has a significant effect on other variables such as potential evapotranspiration, leads to a significant discrepancy between water balance values which are simulated and registered by the hydrographs.

Conclusions. The applicability of Climate Forecast System Reanalysis (CFSR) data to river flow modelling in arid and semi-arid regions such as Eritrea is questionable. The incompatibility of spatial and temporal variations of initial variables (e.g. precipitation), derived from reanalysis data sets and instrumental observations, is undoubtedly the main reason for errors. Thus, the application of reanalysis data sets and development of hydrological models for the region under study requires further intensive research aimed at identifying most effective mechanisms designated for the harmonization of differences between reanalysis data and field observations. In the course of further research, CFSR information is to be converted into more realistic data; climate reanalysis indicators, provided by other sources and designated for different time scales in the context of the “rainfall runoff” model are to be assessed, and the efficiency of other software systems is to be compared with MIKE 11-NAM.

KEYWORDS: Eritrea, reanalysis of the climate forecast system, hydrological simulation, Mereb-Gash, MIKE 11-NAM model, rainfall runoff

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Оценка применимости гидрологического модуля MIKE 11-NAM для моделирования дождевого стока в малоизученном речном бассейне

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АННОТАЦИЯ

Введение. Необходимость моделирования гидрологических процессов обусловлена, в том числе, сложностью гидрологических систем, а также недостаточностью данных из-за отсутствия или малочисленности инструментальных наблюдений. С недавнего времени реанализ климатических сведений, полученных ведущими метеорологическими центрами мира, достаточно успешно используется в регионах с дефицитом инструментальной информации. Настоящая работа направлена на оценку применимости данных реанализа климата для моделирования дождевого стока (осадки – сток) в малоизученном речном бассейне на территории Эритреи.

Материалы и методы. Использовали данные реанализа системы климатических прогнозов (CFSR) Национального центра прогнозирования окружающей среды (США). Также для определения границ водосборов и формирования модели речной сети в рамках таких инструментов, как MIKE и GIS, использовалась топографическая информация высокого разрешения, полученная в ходе реализации международного исследовательского проекта SRTM. Кроме
того, процессы калибрки и валидации (оценивания) гидрологической модели (качество моделирования) выполнялись с применением критерия эффективности Наша-Сатклиффа, коэффициента дисперсии и среднеквадратичной ошибки корня объемных и линковых расходов.

Результаты. Полученные результаты свидетельствуют о том, что заметное завышение количества осадков в массивах данных реанализа, которые, в свою очередь, оказывают существенное влияние на другие переменные, такие как потенциальная аэвапотранспирация, приводит к значительному несоответствию между сформулированным и наблюдаемым гидрографами и водным баланском.

Выводы. Применяемость сведений реанализа системы климатических прогнозов (CFSR) для моделирования речного стока в условиях засушливых и полузасушливых регионов, таких как Эритрея, вызывает некоторые сомнения. Несовместимость пространственных и временных вариаций исходных переменных (например, осадков) из массивов данных реанализа и наземных измерительных наблюдений, несомненно, является основной причиной ошибок. Посему, разработка гидрологических моделей для условий исследуемого региона на основе массивов данных реанализа требует дальнейших интенсивных проработок с целью поиска наиболее эффективных механизмов, позволяющих гармонизировать различия между сведениями реанализа и натуральными наблюдениями. На следующих этапах исследования необходимо выполнить преобразование CFSR-информации в более реалистичные данные, оценить показатели климатического реанализа из других источников для различных временных масштабов в контексте модели «осадки – сток» и провести исследование эффективности иных программных комплексов в сравнении с MIKE 11-NAM.

КЛЮЧЕВЫЕ СЛОВА: Эритрея, реанализ системы климатического прогноза, гидрологическое моделирование, MIKE 11-NAM, осадки – сток

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INTRODUCTION

The complexity of hydrologic systems and the inadequacy of data caused by limitations imposed by currently used measurement techniques [1] have resulted in the advancement of hydrological simulation. The accuracy of hydrological simulation-based predictions relies on the hydrological variability and measurement techniques. Hydrological variations include those of physiographic factors, such as climate, soils, vegetation, topography, geology as well as the growing effect of human activities. Despite their ever growing influence, the application of hydrological simulation keeps expanding its sphere of influence in environmental and water resources areas [2, 3]. Widespread application of hydrological models is primarily caused by swift developments in the computer technology [1–6]. However, there are still water management problems that existing models cannot address with sufficient confidence [2, 7–9]. The reasons for that can be reduced to the two principal factors. Firstly, almost all simulation tools have been primarily developed for boreal areas suggesting that models would possibly be boreal [2, 5, 10]. Despite ambitious global approaches, such as PUB, the majority of success stories were limited to gauged basins. Challenges linked to the lack of appropriate predictions in ungauged basins, especially in arid and semi-arid regions, are yet to be addressed [2, 10]. Secondly, unreliable climate projections and incomplete process understanding have caused substantial uncertainties in projections. Recent studies of predictions made in respect of ungauged basins [9–13] have demonstrated that the presence of global changes in spatio-temporal temperature and precipitation patterns, regional and local changes in river flows and hydro-chemical regimes as a result of combined effects of the climate change, land-use changes and long-term dynamics intrinsic to the hydro-climatic system are some of the constraints that require joint efforts of hydrologists and the society.

Hydrological models have continually evolved since the middle of 19th century. Their history dates back to the rational method followed by single event-based models, for instance, a unit hydrograph [14]. Henceforth, numerous developments followed the unit hydrograph model, such as an instantaneous unit hydrograph [15], the theory of infiltration and overland flow [16, 17], soil conservation services [18], etc. The most renowned of early continuous simulation models is the Stanford watershed model [19], followed by physical data models that encompass the whole hydrological cycle, for example, the European Hydrological System [20] and the topography model [21]. In the meantime, a number of either somewhat less comprehensive or complex models were developed over the years, for example, a hydrological engineering centre [22] and the Tank model [23], the monograph written by Kuchment [24], a deterministic “hydrograph” hydrological model [25], a precipitation runoff modelling system [26], a soil water assessment tool (SWAT) [27], an ecological model for applied geophysics [28], etc. Presently, global climate models are also able to simulate the global hydrological cycle using simplified physics based models. An overview of classified hydrological models is available in the works written by [4]. Refsgaard and Knudsen [29] compared different types of hydrological models in terms of data requirements and model performance. A review of the history, classification, selection, recent developments in hydrological modelling in the context of arid and semi-arid regions is available in [10, 29]. Among various modelling classifications, the lumped

1 ISCS “Supplement A, Section 4, Chapter 10, Hydrology”: in National engineering handbook, Washington, D.C. : USDA, 1956.
conceptual type of mathematical models is the most easily and universally applicable model used in hydrology. In these models, rainfall runoff is based on conceptual representations of physical processes of water movement in the entire catchment area. The examples of such models include the Sacramento model [30], the Tank model [31], the Hydrologiska Byrån’s Vattenbalansavdelning (HBV) model [32], and the MIKE 11-NAM model [33, 34]. However, the scope of this study will be limited to the NAM model (the abbreviation of the Danish “Nedbør-Afstrømnings-Model”, meaning a precipitation runoff model) that was originally developed at the Institute of Hydrodynamics and Water Resources, Technical University of Denmark. It is a deterministic, lumped, conceptual mathematical model based on a set of linked mathematical statements, describing the behaviour of the land phase of the hydrological cycle2 [35].

The NAM model has been used by many researchers [36, 37] to simulate the runoff from gauged and ungauged catchments. For example, three modelling systems were compared in [36]: a lumped conceptual rainfall runoff modelling system (NAM), a semi-distributed hydrological modelling system (WATBAL), and a distributed physics based hydrological modelling system (MIKE SHE). The results have proven the usefulness of a model designated for runoff predictions in basins having different hydrological regimes and climatic settings around the world. The NAM model could also be utilized for various other purposes; for example, it could help to optimize water supply and water management in irrigation and drainage systems [38].

Extensive studies of integrated water resources in the Mereb-Gash river basin are yet to be performed.

So far, only a handful of studies [39–41] attempt to understand the hydrology of the area. Others [42, 43] have assessed the environmental impacts of flooding and downstream and possible mitigation mechanisms. These modelling efforts range from simple conceptual hydrological models to distributed physics based complex models. One of the main challenges tackled by all these studies is the acute shortage of hydrometeorological data, resulting in the unreliability and uncertainties of model outputs. Under these circumstances, global reanalysis products are to fill the gap in data scarce regions [44–48]. Therefore, numerous studies [44–46] verified the usefulness of CFSR in hydrological modelling.

The objective of this paper, therefore, is to assess the applicability of the NAM rainfall runoff model to runoff simulations and water balance estimations in appropriate locations within the Mereb-Gash river basin in Eritrea. To this end, CFSR reanalysis datasets are used to obtain model input variables.

MATERIALS AND METHODS

Description of the research area

This study is focused on the Mereb-Gash river basin, having an outlet near Kassala town in Sudan. It is a transboundary river basin, originating from Mount Teqera, south-west of the capital city of Asmara, Eritrea (Fig. 1). Nearly 75% of the total area (22,849.60 km²) lies in the Eritrean territory3. Geographically, the outlet selected for this study is located at 36.39° E and 15.45° N. The elevation varies from over 3,200 m in the Ethiopian highland to 517 m above the mean sea

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2 DHI “A Modelling System for Rivers and Channels Reference Manual”. 2017.

3 Euroconsult, “Sector study on national water resources and irrigation potential: component 1 report surface water resources,” Arnhem, Netherlands, 1998
level in the outlet area. The basin is long (the length of the main channel is about 500 km) and narrow; its shape is elongated, and its topography is undulating. The waters of the Mereb-Gash river don’t usually reach the Nile river; rather, they are lost in the sands of the eastern plains of Sudan. The official reports issued by the Water Resources Department (Eritrea) indicate that the climate and the flow vary in the basin. The mean annual flow is estimated to be 680 million m$^3$ [43] and the maximum flow rate is 1,000 m$^3$s$^{-1}$ [44]. It is dry during most of the year but it is exposed to flash floods in rainy seasons, transporting 40 million m$^3$ of sediment. The rainy season usually starts in June and ends in September; it brings several flood flows; for example, the return period of severe floods in Kassala town is 1 to 5 years [43]. Similarly, western plain areas in Eritrea had been repeatedly exposed to flooding. A long-term annual rainfall usually ranges from over 900 mm to less than 300 mm$^1$. The rainfall is considered as a moderate to high intensity event of short duration with a limited coverage. The coverage appears to be always below 20–30 km and even smaller$^1$. The temperature is highest in April and May and lowest in December and January, ranging from below 10 °C in the highlands to more than 45 °C in the lowlands.

**Description of the NAM model**

MIKE 11 is a powerful hydrological modelling system used to solve multi-component water management problems. It has several modules, including hydrodynamic and advection-dispersion units, sediment transport facilities, MIKE Eco lab, a flood forecasting facility, a rainfall runoff unit, etc. In some cases, they can be used either in combination with other modules or as standalone simulators [35]. MIKE 11 has different types of rainfall runoff models, such as NAM, a hydrodynamic model, a soil moisture meter and a soil conservation facility collectively used to assess the storm runoff, etc. As it was mentioned in the preceding section, the scope of studies covered by this article is limited to the NAM model.

NAM simulates overland flow, interflow, and baseflow components as a function of the moisture contents in different storage systems. It is applicable independently or together with other modules. NAM has the potential to handle either a single catchment or a large river basin that has numerous sub-catchments and a complex network of river channels within the same modelling framework. Conceptual models (for example, a unit hydrograph [14] and NAM) rely on the laws of physics and semi-empirical regularities. Being a lumped-element model, NAM ignores the spatial variability of variables and parameters, thereby treating each catchment as a single unit. Thus, the parameters and variables represent average values for the entire catchment. While a typical range of likely parameter values can be provided in certain cases, it is not always possible to determine all parameters based on climate and catchment characteristics. Thus, the final parameter estimation must be performed by calibration against measured data. Table 1 lists the basic parameters of the NAM model and their brief descriptions.

**Model structure**

The schematic representation of the NAM model structure is shown in Fig. 2. It has various components of hydrological processes in four different and interconnected storage reservoirs: the snow storage reservoir, the surface storage reservoir, the lower zone (root zone) storage reservoir, and the groundwater storage reservoir. Additionally, the model takes account of artificial interventions into hydrological processes, such as irrigation, junior water, and dam water. The model is based on a linear reservoir model with time constants $\tau_{OF}$, $\tau_{TIF}$, and $\tau_{TOF}$. The model structure is shown in Fig. 2.

**Table 1. Basic parameters of the NAM model**

| Parameter | Description |
|-----------|-------------|
| $U_{\text{max}}$ | The upper limit of the amount of water in the surface water storage reservoir. It is the water content in interception storage, depression storage, and surface storage reservoirs. It is continuously lost to evaporation, interflow, and infiltration. The typical values of $U_{\text{max}}$ are in the range of 10–20 mm |
| $L_{\text{max}}$ | Maximum water content in the lower zone storage. It represents soil moisture below the surface from which plants take water for transpiration. As a rule, $U_{\text{max}} = 0.1 \times L_{\text{max}}$, where $L_{\text{max}}$ is in the range of 100–300 mm |
| $CQOF$ | Overland flow runoff coefficient. $CQOF$ values are in the range of 0 and 1 and determine the distribution of excess rainfall between the overland flow and infiltration |
| $CK_{\text{OF}}$ | Time constant for the interflow from the surface storage reservoir. $CK_{\text{OF}}$ is the dominant routing parameter of the interflow because $CK_{\text{OF}} > CK_{\text{OF}}$. $CK_{\text{OF}}$ values are in the range of 500–1,000 hours |
| $CK_{\text{TIF}}$ | Time constant for overland flow and interflow routing. The overland flow and the interflow are routed through two successive linear reservoirs with time constants $CK_{\text{TIF}}$. Typical values are in the range of 3–48 hours |
| $TOF$, $TIF$, $TG$ | Threshold values for overland flow, interflow, and groundwater recharge, respectively. The flow is only generated if the relative moisture content in the lower storage zone is above the threshold value. Their values are in the range of 0–1 |
| $CK_{\text{BF}}$ | Time constant for baseflow routing. The baseflow from the groundwater storage reservoir is generated using a linear reservoir model with time constant $CK_{\text{BF}}$. $CK_{\text{BF}}$ values are in the range of 500–5,000 hours |
as irrigation and groundwater pumping. Ultimately, the model produces output, i.e., catchment runoff, as well as the information about other elements that comprise the land phase of the hydrological cycle, such as the temporal variation of evapotranspiration, soil moisture content, groundwater recharge, and groundwater levels.

**Model calibration objectives**

In this work, both manual and automatic calibration procedures were employed with consideration for four calibration objectives. An automatic optimization routine based on a multi-objective optimization strategy, in which four objectives can be simultaneously optimized, is part of the NAM model. These objectives relate to coherence between different simulated and observed characteristics of hydrographs, including timing, rate and volume. Hydrograph characteristics include water balance, shape, peak and low flows. In manual calibration, a trial-and-error parameter was employed so that the goodness-of-fit of the calibrated model could be identified based on the visual examination by means of comparing simulated and observed hydrographs. Manual calibration has the advantage of adjusting parameters except for those listed in Table 1 and whenever one of the objectives takes priority over other ones [35]. On the other hand, calibration objectives are formulated as numerical goodness-of-fit measures that are optimized automatically. Numerical performance measures for four calibration objectives proposed by [49] are provided in equations (1) through (4):

The overall volume error

\[ F_1(\theta) = \frac{1}{N} \sum_{i=1}^{N} \left( Q_{\text{obs},i} - Q_{\text{sim},i}(\theta) \right) \]  

(1)

The overall root mean square error (RMSE)

\[ F_2(\theta) = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( Q_{\text{obs},i} - Q_{\text{sim},i}(\theta) \right)^2 \right]^{1/2} \]  

(2)

The average RMSE of peak flow events

\[ F_3(\theta) = \frac{1}{M_p} \sum_{j=1}^{M_p} \left[ \frac{1}{n_j} \sum_{i=1}^{n_j} \left( Q_{\text{obs},i} - Q_{\text{sim},i}(\theta) \right)^2 \right]^{1/2} \]  

(3)

The average RMSE of low flow events

\[ F_4(\theta) = \frac{1}{M_l} \sum_{j=1}^{M_l} \left[ \frac{1}{n_j} \sum_{i=1}^{n_j} \left( Q_{\text{obs},i} - Q_{\text{sim},i}(\theta) \right)^2 \right]^{1/2} \]  

(4)

where \( Q_{\text{sim}} \) and \( Q_{\text{obs}} \) is a simulated and observed discharge at time \( i \), respectively; \( N \) — the total number of time steps in the calibration period; \( M_p \) and \( M_l \) — the number of peak and low flow events, respectively; \( n_j \) — the number of time steps within peak/low flow event number \( j \); and \( \theta \) — the set of model parameters to be calibrated.

Although the overall water balance error and overall RMSE are normally applied in general hydrological studies, high and low flow RMSE enjoyed equal attention. According to DHI [35], the goodness-of-fit of the calibrated model is basically affected by errors in meteorological input data, errors in recorded observations, errors...
and simplifications inherent in the model structure, and errors caused by the use of non-optimal parameter values. The fact that the objective of the study was to assess the applicability of CFSR reanalysis datasets to runoff simulations, errors due to non-optimal parameters could only be handled at this stage. The length of the available streamflow data used for calibration and validation was another limitation in some cases. Normally, satisfactory calibrations require continuous observations of runoff for a period of 3–5 years. However, runoff series of a shorter duration will also be useful for calibration, although they do not ensure efficient model calibration [35]. It is recommended to validate the model with the help of the data not used in model calibration to ensure proper evaluation of its reliability and hydrological soundness. Hence, the split-sample test method is applied.

**Evaluation measures**

Simulated runoffs were compared with discharge measurements to evaluate the calibrated model. As it was described earlier, both graphical and numerical performance measurements were applied in the calibration process. Graphical evaluation means comparison between simulated and observed hydrographs, on the one hand, and between simulated and observed runoffs, on the other hand. Numerical performance measurements include the overall water balance error (i.e. the difference between average simulated and observed runoffs), and the measurement of the overall shape of the hydrograph based on the Nash-Sutcliffe efficiency (NSE) [50] according to

\[
NSE = 1 - \frac{\sum_{i=1}^{N} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{N} (Q_{obs,i} - \bar{Q}_{obs})^2},
\]

where \(Q_{sim,i}\) and \(Q_{obs,i}\) stand for the simulated and observed discharge during time \(i\), respectively; and \(\bar{Q}_{obs}\) stands for the average observed discharge. Nash – Sutcliffe efficiency can range from \(-\infty\) to 1. An efficiency of 1 (NSE = 1) corresponds to perfect convergence between the simulated runoff and the observed data, the zero efficiency value (NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas the efficiency value below zero (NSE < 0) occurs when the observed mean is a better predictor than the model. Threshold values indicating a model of sufficient quality are within the range of 0.5 < NSE < 0.65.

**Data-related requirements**

Input data include model parameters, initial conditions, meteorological data, and streamflow data. Even though rainfall and potential evapotranspiration are the most important data, temperature and radiation can be taken account of, depending on the presence or absence of snow. However, as the study is focused on arid and semi-arid climatic conditions, snow could be neglected. NAM model also offers an option to incorporate irrigation and groundwater pumping activities as part of the modelling process. However, these issues were excluded from the study for the two main reasons. Firstly, although the detailed historical background information on irrigation and groundwater in the basin was unavailable, major diversion structures, large reservoirs, hydropower plants and water consumers that could significantly affect the magnitude of the streamflow were unavailable during the reanalysis period. The renowned diversion structure at Teseney established in 1928 during the Italian colonial era is the only exception. A vast agricultural development project in Aligidir was to irrigate approximately 10,000 hectares of land. However, its operation was hampered primarily due to pre- and post-independence wars. Apart from the limited information about the efforts to revitalize the project, its current status, water consumption, extent and type of irrigation are yet unknown. Nonetheless, most of the agricultural practices within the basin predominantly relied on seasonal rainfalls, i.e., modern technology-based irrigation projects hardly existed. In this regard, DHI [35] recommends that minor irrigation schemes within a catchment may be neglected as they normally have little influence on catchment hydrology. Secondly, groundwater was the main source of water for different uses. As for the part of the Mereb-Gash river basin, characterized by relatively low evapotranspiration, rugged topography and poor soil formations, groundwater supply is supplemented by surface waters stored in small reservoirs and ponds outside the main river channel. Keeping the above facts in mind, two approaches were implemented in the NAM model operation: (i) operation without irrigation and pumping and (ii) operation that includes irrigation and pumping. Rainfall, potential evapotranspiration and streamflow for calibration and validation were applied to both approaches.

Generally, the time scale of rainfall and potential evapotranspiration depends on the purpose of the study and on the time scale of the catchment response. Based on the DHI [35] recommendations, daily and monthly values of rainfall and potential evapotranspiration were used in model calibration and accuracy evaluation. Different time scales (hourly and daily) of the streamflow data were used depending on their availability at stream gauging stations near Kassala, Gherger, and Gala Adi-Ifnas. Given the scarcity of data, CFSR datasets, which are available at the 38 km resolution, were supplied by the National Centres for Environmental Prediction — CFSR. The information, covering the period between 1979 and the middle of 2014, was collected from 32 stations. A CFSR-based spatial and statistical variability analysis of Mereb-Gash has recently been studied by a group of co-authors [41]. Following their recommendation on the suitability of potential evapotranspiration estimation methods, Penman-Monteith equation was employed. Moreover, a high-resolution digital elevation dataset for the study area, available from the shuttle radar topography mission at the global resolution of 1 arc-second, was used for catchment delineation and stream network formations in MIKE zero and QGIS.
Model setup

Rainfall, potential evapotranspiration and streamflow time series were prepared in the required formats for the NAM model. However, the fact that the NAM model simulates the rainfall runoff process in a lumped way, there was a need to combine rainfall and evapotranspiration data from different stations within and around a single catchment, into a single time series of weighted averages. The resulting time series represented mean area values of aforementioned model input variables for a catchment. The Thiessen polygon method was intuitively selected among other available options (for example, isohyetal method). Fig. 3 shows the NAM model set up for the study area. The partitioning of the whole basin into sub-catchments was done bearing in mind the limitations of lumped models, that is, they cannot be applied to catchments having larger areas because of the assumption of the spatial uniformity of variables. For example, the maximum area that a unit hydrograph (one of well-known lumped models) should be applied to, is less than 5,000 km². Moreover, previous works, based on the intensive survey and understanding of the catchment climate, geology, physiography were also taken into account to some extent. Thiessen polygon weightages from 32 stations, having the total area of 22,849.60 km², are presented in Table 2. The station that

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**Table 2. Thiessen polygon weightages of sub-catchments**

| Sub-catchment       | Area, km² | Weightage |
|---------------------|-----------|-----------|
| Ghengeria           | 561.00    | 0.92 0.04 | 0.04 — — |
| Gala Adi-Nfas       | 329.90    | 0.10 0.88 | 0.02 — — |
| Mai-Aini            | 624.10    | 0.02 0.11 | 0.65 0.22 | — — |
| Ona-Gabion          | 1,225.90  | 0.09 0.17 | 0.49 0.24 | 0.01 — |
| Adi-Keih-Tsorona    | 569.30    | 0.56 0.33 | 0.10 0.01 | — — — |
| Tsorona-1           | 637.70    | 0.02 0.13 | 0.75 0.10 | — — — |
| Kolobordo           | 523.10    | 0.40 0.14 | 0.41 0.06 | — — — |
| Ksad-Iqa            | 1,496.10  | 0.21 0.56 | 0.22 0.01 | — — — |
| Adi-Ghelae          | 2,887.10  | 0.05 0.29 | 0.02 0.26 | 0.22 0.16 — |
| Adi-Chigono         | 2,658.20  | 0.23 0.02 | 0.12 0.04 | 0.30 0.06 0.23 |
| Shambiko            | 2,946.20  | 0.28 0.24 | 0.02 0.39 | 0.06 0.01 — |
| Tokombia            | 2,388.70  | 0.02 0.04 | 0.19 0.42 | 0.30 0.03 — |
| Haikota             | 1,486.40  | 0.33 0.07 | 0.56 0.04 | — — — |
| Teseney             | 3,288.20  | 0.03 0.07 | 0.31 0.35 | 0.11 0.12 0.01 |
| Kassala             | 1,227.70  | 0.11 0.03 | 0.04 0.44 | 0.38 — — |

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**Fig. 3. NAM model set up for Mereb-Gash river basin**
was nearest to the sub-catchment under consideration had the largest influence and vice versa. Accordingly, each sub-catchment has a limited number of stations that contributed to average model input values. During the calibration of the NAM model, automatic calibration augmented by trial and error adjustment was performed in respect of each sub-catchment so as to obtain the optimal parameters with the best match between simulated and observed data. After the calibration process was completed, the model was verified at the sub-catchments selected for that purpose.

**RESULTS AND DISCUSSION**

In the preceding section, it was pointed out that two approaches were applied to calibration processes; they either included or failed to include irrigation and groundwater pumping. In the first case, the fact that real time and space data were missing, their effects on simulated runoffs were studied by assuming variable irrigation areas and groundwater extraction amounts. It was identified that these had no significant influence on simulated outputs generated by the NAM model, which fact was in line with the DHI [35] recommendations described in the preceding section. Thus, the discussion henceforth will focus on the second case, i.e., runoff simulation disregarding irrigation and groundwater pumping.

It was impossible to obtain parameters for each sub-catchment: two of the three stations, whose streamflow data are used for calibration and verification, are located close to each other. Therefore, the use of global parameters was the only viable option. Optimal parameters of Ghergera and Gala Adi-Nfas were applied to upper sub-catchments in the Mereb-Gash basin. These sub-catchments are characterized by relatively low potential evapotranspiration, low infiltration rate, and high runoff coefficient. On the contrary, remaining sub-catchments were assumed to have relatively better water retaining potentials, (thus, reducing the runoff coefficient value) higher infiltration rates and potential evapotranspiration. Consequently, corresponding parameters of automatic calibration algorithms were manually fine-tuned so that the combined simulated runoff became as close to the observed flow at the outlet (Kassala) as possible. Given these assumptions, the water balance, observed and simulated data provided by hydrographs, numerous calibration trials were performed. Ultimately, basic parameters identified by means of automated calibration, were adjusted and manually refined (Table 3).

According to Table 3, a smaller value of \( CQOF = 0.50 \) were obtained for a relatively flat catchment having coarse, sandy soils and a large unsaturated zone, whereas large \( CQOF = 0.70 \) was obtained for catchments with probably low, permeable soils, such as clay or bare rocks. Peak runoff events are caused by intensive overland flows. The peak volume was adjusted by changing the overland flow runoff coefficient \( (CQOF) \), whereas the shape of the peak was dependent on the time constant used in runoff routing \( (CK) \). Similarly, surface and root zone storages \( (U_{max}, L_{max}) \) were identified as the major parameters that affected evapotranspiration; the higher these values, the higher the rate of evapo-

**Table 3.** NAM model’s basic parameters for the Mereb-Gash basin

| Sub-catchment          | Parameter | \( U_{max} \) | \( L_{max} \) | \( CQOF \) | \( CK_F \) | \( CK_{12} \) | \( TOF \) | \( TIF \) | \( TG \) | \( CK_{gp} \) |
|-----------------------|-----------|---------------|---------------|-----------|-----------|-----------|---------|---------|---------|-----------|
| Ghergera              |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Gala Adi-Nfas         |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Mai-Aini              |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Ona-Gabion            |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Adi-Keih-Tsorona      |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Tsonora               |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Koloburdo             |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Ksad-Iqa              |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Adi-Ghelae            |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Adi-Chigono           |           | 15.20         | 194           | 0.70      | 1.000     | 47.70     | 0.90    | 0.90    | 0.40    | 3.000     |
| Shambiko              |           | 20.00         | 300           | 0.50      | 1.000     | 30.00     | 0.90    | 0.90    | 0.50    | 3.000     |
| Tokombia              |           | 20.00         | 300           | 0.50      | 1.000     | 30.00     | 0.90    | 0.90    | 0.50    | 3.000     |
| Haikota               |           | 20.00         | 300           | 0.50      | 1.000     | 30.00     | 0.90    | 0.90    | 0.50    | 3.000     |
| Teseney               |           | 20.00         | 300           | 0.50      | 1.000     | 30.00     | 0.90    | 0.90    | 0.50    | 3.000     |
| Kassala               |           | 20.00         | 300           | 0.50      | 1.000     | 30.00     | 0.90    | 0.90    | 0.50    | 3.000     |
transpiration and vice versa. Similarly, the base flow is affected by other runoff components; a decrease in the overland flow or the interflow causes a higher baseflow, and vice versa. The shape of the baseflow recession is a function of the baseflow time constant (\( CK_{BF} \)). Changes in root zone threshold values \( TOF \) and \( TIF \) were not significantly affecting the results; hence, the same values were applied. However, \( TG \) values were slightly different for upper and lower portions of the basin.

Calibration data-based runoff rates and accumulated volumetric runoffs are presented in Fig. 4 for three stations. In Fig. 4 (a, b and c), simulated and observed runoff hydrographs for Gala Adi-Nfas, Ghergera and Kassala (combined)\(^4\) are provided. The time span of the recorded flow at Ghergera was limited to one rainy season; hence, it is difficult to draw conclusions with certainty. Although the accumulated runoff (Fig. 4, e) shows better results as compared to other two options; its corresponding simulated and observed hydrographs (Fig. 4, b) do not match in all aspects. Hydrographs from Gala Adi-Nfas and Kassala (Fig. 4 a and c) seem to capture the flow seasonality, although they do it with substantial volumetric and peak (low and high) discrepancy in terms of the flows. These discrepancies are clearly magnified in terms of accumulated runoffs shown in Fig. 4 (a and f). Moreover, all simulated hydrographs have demonstrated another point; that’s the presence of the baseflow even in dry periods.

Parameters assigned to each sub-catchment covered by calibration processes (Table 3) were used in validation. Accordingly, simulated and observed runoff hydrographs for Gala Adi-Nfas, Ghergera and Kassala, were obtained as shown in Fig. 5 (a, b and c). The discrepancy between simulated and observed hydrographs is worse than the calibration results (Fig. 4); the timing, the rate of high and low peaks, the volume, and the shape of hydrographs are totally different from observed runoffs.

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\(^4\) Kassala (combined) represents a runoff from a set of all the sub-catchments to be further used in the ensuing discussions.
Assessment of applicability of MIKE 11-NAM hydrological module for rainfall runoff modelling in a poorly studied river basin

Fig. 4. Simulated and observed runoff rates and corresponding accumulated runoffs at selected stations in the aftermath of calibration processes at (i) Gala Adi-Nfas (a and b), (ii) Ghergera (c and d), and (iii) Kassala (e and f).

NSE, water balance and RMSE calibration and validation evaluation (Table 4) comply with the conclusion drawn from the graphical observation discussed earlier. Most of the NSE values are below zero meaning that the observed mean is a better predictor than the model. Moreover, the water balance also depicts a significant discrepancy between simulated and observed runoffs with the exception of Ghergera. RMSE values are above zero, thus, representing an imperfect convergence between observed and simulated runoffs. Similarly, other accuracy factors are presented in Table 5. Most of the measurements have proven NAM’s poor performance in the area of interest.

What could be the reason for the unsatisfactory performance of the NAM model? To answer this question, one should think about evaluating various sources of errors discussed in the Materials and methods section. Let’s dwell on the errors that originate from the reanalysis data, since other sources of errors are either manageable (for example, selection of non-optimal parameters) or unmanageable (for example, errors in recorded observations and errors and simplifications inherent in the model structure) for obvious reasons. In view of this fact, reanalysis (or satellite-based) data were compared with ground based rainfall data. Table 6 shows rainfall frequency values during rainy months over the period of 2004 to 2006 provided by ground-based and satellite-based stations in the Ghergera catchment, which are located close to each other (approximately 7 km apart). If we look at the satellite-based number of rainy days, it turns clear that in the months of July and August, the probability of a rainfall is approximately 100%. However, the probability of a rainfall according to ground-based station is below 50%. When minor rainfalls (< 5 mm) are excluded, the rainfall frequency prognosticated by the satellite is by far higher than the one prognosticated on Earth, especially in the months of July and August when the peak runoff occurs. The same observation was made in respect of all selected stations even in dry periods when a rainfall was less likely to occur. Therefore, it gives sense to associate the
Table 4. Calibration and validation evaluation figures

| Sub-catchment | Calibration | Validation |
|---------------|-------------|------------|
|               | Water balance | RMSE       | NSE  | Water balance |
|               | Observed, mm/year | Simulated, mm/year |     | Observed, mm/year | Simulated, mm/year |
| Ghergera      | 0.13 | 1.20 | 1.20 | 9.752 | –34.61 | 1.0 | 8.4 |
| Gala Adi-Nfas | –4.28 | 6.50 | 14.70 | 7.77 | –2.23 | 3.4 | 16.8 |
| Kassala       | –9.74 | 3.50 | 22.00 | –96.67 | 1.6 | 22.1 |

Table 5. Calibration and validation accuracy factors

| Accuracy factors      | Calibration | Validation |
|-----------------------|-------------|------------|
|                       | Kassala | Gala Adi-Nfas | Ghergera | Kassala | Gala Adi-Nfas | Ghergera |
| Correlation factor    | 0.531 | 0.349 | 0.357 | 0.017 | 0.163 | 0.015 |
| Peak error            | 0.178 | 5.197 | 1.143 | –0.981 | 0.784 | –0.754 |
| Volume error          | 5.016 | 1.753 | 5.016 | 213.88 | 4.716 | 8.013 |
| Peak time error       | –1142.208 | 0.000 | –11 | –8.00 | 354 | 9.000 |

Table 6. Frequency of rainy days prognosticated by ground- and satellite-based stations in Ghergera catchment

| Year | Month | Number of rainy days | Number of rainy days > 5 mm |
|------|-------|----------------------|-----------------------------|
|      |       | Ground-based | Satellite-based | Ground-based | Satellite-based |
| 2004 | Jul   | 9           | 29             | 6           | 5              |
|      | Aug   | 10          | 27             | 5           | 18             |

Fig. 5. Simulated and observed runoffs in the aftermath of validation processes: a — Gala Adi-Nfas, b — Ghergera (in 2007); c — Kassala (2011 and 2012)
Assessment of applicability of Mike 11-NAM hydrological module for rainfall runoff modelling in a poorly studied river basin

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poor performance of the NAM model with the overestimation of satellite-based rainfall measurements.

Graphical analyses of satellite- and ground-based rainfall stations were also conducted to understand their relationships. For the sake of illustration, correlations between the two sources of measurements are provided in Fig. 6. The analysis indicates poor correlation \( r = 0.364 \) in terms of the annual rainfall (Fig. 6, a), whereas a strong correlation \( r = 0.984 \) could be observed in terms of the monthly rainfall (Fig. 6, b). Most of the analyzed stations demonstrated more or less similar patterns.

CONCLUSIONS

In this work, the applicability of the NAM model to the simulation of runoffs from the ungauged basin in arid and semi-arid regions, such as the Mereb-Gash river basin in Eritrea, using CFSR datasets, has been proven unreliable. Evaluation measures have proven the unsatisfactory performance of the model, and this conclusion differs from the findings of earlier studies [9–13]. Various sources of errors that could affect the goodness-of-fit of the calibrated model, the incompatibility of spatial and temporal variations of input variables extracted from reanalysis datasets and ground-based observations are undoubtedly among the primary sources of errors. CFSR datasets noticeably overestimated rainfall values which, in turn, affected corresponding input variables. We believe that it is too premature to consider this study as a strong argument to reject reanalysis datasets in runoff projections in arid and semi-arid areas. Rather, bearing in mind the resourceful nature of reanalysis datasets, on the one hand, and the shortage of reliable ground-based data, on the other hand, other mechanisms that can produce

| Year | Month | Number of rainy days | Number of rainy days > 5 mm |
|------|-------|-----------------------|-----------------------------|
|      |       | Ground-based | Satellite-based | Ground-based | Satellite-based |
| 2004 | Sep   | 3           | 7               | 2              | 0              |
|      | Oct   | 3           | 6               | 2              | 0              |
|      | Jun   | 0           | 15              | 0              | 4              |
|      | Jul   | 13          | 30              | 6              | 24             |
|      | Aug   | 15          | 28              | 12             | 17             |
|      | Sep   | 2           | 14              | 1              | 1              |
|      | Oct   | 0           | 2               | 0              | 0              |
| 2005 | Jun   | 0           | 14              | 0              | 0              |
|      | Jul   | 11          | 31              | 8              | 23             |
|      | Aug   | 13          | 31              | 7              | 22             |
|      | Sep   | 5           | 14              | 3              | 4              |
|      | Oct   | 3           | 7               | 2              | 2              |

Fig. 6. Comparison of satellite-based and ground-based rainfall measurements taken at the stations in the Ghergera catchment, which are located close to each other: a — annual; b — monthly
better projections, need to be researched. For example, the effects of climate reanalysis sources and the time scale of runoff simulations could serve as the starting point. Furthermore, numerous sources [2, 10, 29] have proven that so far there is no universal model for runoff simulations. Thus, CFSR reanalysis datasets need to be studied using other hydrological models (for example, SWAT), and appropriate hydrological modelling tools applicable to the area can be identified. The findings have also proven the uncertainty about global climate projection methods. Therefore, the co-authors would like to stress the need to enhance conventional hydro-meteorological data collection methods, such as rain and stream gauges.

REFERENCES

1. McGlynn B.L., Blöschl G., Borga M., Borrmann H., Hurkmans R., Komma J., Nandagiri L. et al. A data acquisition framework for runoff prediction in ungauged basins. Runoff Prediction in Ungauged Basins, 2013; 29-52. DOI: 10.1017/eb09781139235761.006

2. Wheater H., Sorooshian S., Sharma K.D. Hydrological Modelling in Arid and Semi-Arid Areas. New York, Cambridge University Press, 2008.

3. Sivapalan M., Takeuchi K., Franks S.W., Gupta V.K., Karambiri H., Lakshmi V. et al. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal, 2003; 48(6):857-880. DOI: 10.1623/hysj.48.6.857.51421

4. Refsgaard J.C., Abbott M.B. The Role of Distributed Hydrological Modelling in Water Resources Management. Distributed Hydrological Modelling. Water Science and Technology Library, 1996; 22:1-16.

5. Mekoena M.P., Kapangaziwiri E., Kahinda J.M., Hughes D.A. ECOMAG Model: an evaluation for use in South Africa. WRC Report No. TT 555/13, 2013.

6. Kapangaziwiri E., Hughes D.A., Wagener T. Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa. Hydrological Sciences Journal, 2012; 57(5):1000-1019. DOI: 10.1080/02626667.2012.690881

7. Hughes D.A. Three decades of hydrological modelling research in South Africa. South African Journal of Science. 2004; 100:638-642.

8. Tegegne G., Park D.K., Kim Y. Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin. Journal of Hydrology: Regional Studies, 2017; 14:49-66. DOI: 10.1016/j.jhyre.2017.10.002

9. Hrachowitz M., Savenije H.H.G., Blöschl G., McDonnell J.J., Sivapalan M., Pomeroy J.W. et al. A decade of Predictions in Ungauged Basins (PUB) — a review. Hydrological Sciences Journal, 2013; 58(6):1198-1255. DOI: 10.1080/02626667.2013.803183

10. Ghebrehiwot A.A., Kozlov D.V. Hydrological modelling for ungauged basins of arid and semi-arid regions: review. Vestnik MGSU [Proceedings of Moscow State University of Civil Engineering]. 2019; 14(8):1023-1036. DOI: 10.22227/1997-0935.2019.8.1023-1036

11. Montanari A., Young G., Savenije H.H.G., Hughes D., Wagener T., Ren I.L. et al. “Panta Rhei — Everything Flows”: Change in hydrology and society — The IAHS Scientific Decade 2013–2022. Hydrological Sciences Journal. 2013; 58(6):1256-1275. DOI: 10.1080/02626667.2013.809088

12. Mount N.J., Maier H.R., Toth E., Elshorbagy A., Solomatine D., Chang F.-J. et al. Data-driven modelling approaches for socio-hydrology: Opportunities and challenges within the Panta Rhei Science Plan. Hydrological Sciences Journal. 2016; 1-17. DOI: 10.1080/02626667.2016.1159683

13. McMillan H., Montanari A., Cudennec C., Savenije H., Kreibich H., Krueger T. et al. Panta Rhei 2013–2015: global perspectives on hydrology, society and change. Hydrological Sciences Journal. 2016; 1-18. DOI: 10.1080/02626667.2016.1159308

14. Sherman L.K. Streamflow from Rainfall by Unit-Graph Method. Eng. News-Record, 1932; 108:501-505.

15. Nash J.E. *The form of the instantaneous unit hydrograph*. International Association of Hydrological Sciences, 1957; 45(3):114-121.

16. Horton R.E. The role of infiltration in the hydrologic cycle. Transactions, American Geophysical Union, 1933; 14(1):446. DOI: 10.1029/tr014i001p00446

17. Horton R.E. Analysis of runoff-plat experiments with varying infiltration-capacity. Transactions, American Geophysical Union. 1939; 20(4):693. DOI: 10.1029/tr021i004p00693

18. Crawford N.H., Linsley R.K. *The synthesis of continuous stream flow hydrographs on a digital computer*. California, Tech. Rep. No. 12, 1962.

19. Abbott M.B., Bathurst J.C., Cunge J.A., O’Connell P.E., Rasmussen J. An introduction to the European Hydrological System — Systeme Hydrologique Europeen, ‘SHE’, 1: History and philosophy of a physically-based, distributed modelling system. Journal of Hydrology. 1986; 87(1-2):45-59. DOI: 10.1016/0022-1694(86)90114-9

20. Beven K.J., Kirkby M.J. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin. 1979; 24(1):43-69. DOI: 10.1080/02626667909491834
21. Dawdy D.R., O'Donnell T. Mathematical models of catchment behaviour. *Journal of the Hydraulics Division*. 1965; 91(4):123-137.

22. Sugawara M. The flood forecasting by a series storage type model. International Symposium on Floods and their Computation, 1967; 1-6.

23. Kuchment L.S. Mathematical modeling of river flow. Leningrad, Gidrometeoizdat, 1972; 191. (rus.).

24. Vinogradov Yu.B. Issues of hydrology of rain floods in small catchments of Central Asia and South Kazakhstan. Leningrad, Gidrometeoizdat, 1967; 262. (rus.).

25. Leavesley G.H., Lichty R.W., Troutman B.M., Saindon L.G. Precipitation-runoff modeling system: User's manual. US Geological Survey Water-Resources Investigations Report 83-4238, Reston, 1983; 207.

26. Arnold J.G., Srinivasan R., Muttsiah R.S., Williams J.R. Large area hydrologic modeling and assessment. Part I: Model development. *Journal of the American Water Resources Association*. 1998; 34(1):73-89. DOI: 10.1111/j.1752-1688.1998.tb05961.x

27. Motovilov Yu.G., Gottschalk L., Engeland K., Belokurov A. *ECOMAG*-regional model of hydrological cycle. Application to the NOPEX region. Oslo, Department of Geophysics, University of Oslo P.O. Box 1022 Blindern 0315, 1999; 88.

28. Singh V.P., Woolhiser D.A. Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering*. 2002; 7(4):270-292. DOI: 10.1061/(asce)1084-0699(2002)7(4(270).

29. Burnash R. The NWS river forecast system-catchment modelling. Computer Models of Watershed Hydrology, Colorado, Water Resources Publications, 1995; 311-366.

30. Sugawara M. et al. Tank model and its application to Bird Creek, Wollombi Brook, Bikin River, Katsu River, Sanaga River and Nam Mune. Research Note of the National Research Center for Disaster Prevention, 1974; 1-64.

31. Bergstrom S. The HBV model. Computer Models in Watershed Modeling, Colorado, Water Resources Publications, 1995; 443-476.

32. Nielsen S.A., Hansen E. Numerical simulation of the rainfall-runoff process on a daily basis. *Hydrology Research*. 1973; 4(3):171-190. DOI: 10.2166/hh.1973.0013

33. Hann K., Madsen M.N., Dorge J. *MIKE-11* a generalized river modelling package. Computer Models of Watershed Hydrology, Colorado, Water Resources Publications, 1995; 733-782.

34. Refsgaard J.C., Knudsen J. Operational validation and intercomparison of different types of hydrological models. *Water Resources Research*. 1996; 32(7):2189-2202. DOI: 10.1029/96wr00896

35. Madsen H. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. *Journal of Hydrology*. 2000; 235(3-4):276-288. DOI: 10.1016/s0022-1694(00)00279-1

36. Buber A.L. Methodological approaches to solving the problems of multicriteria optimization for the management of water resources of river basins in the interests of water users of the agro-industrial complex (AIC). Moscow, All-Russian Research Institute of Hydraulic Engineering and Land Reclamation named after A.N. Kostyakova, 2018; 75-89. (rus.).

37. Kozlov D.V., Ghebrehiwot A.A. Efficacy of digital elevation and Nash models in runoff forecast. *Magazine of Civil Engineering*. 2019; 87(3):103-122. DOI: 10.18720/MCE.87.9

38. Ghebrehiwot A., Kozlov D. GIUH-Nash based runoff prediction for Debarwa catchment in Eritrea. *E3S Web of Conferences*. 2019; 97:05001. DOI: 10.1051/e3sconf/20199705001

39. Ghebrehiwot A.A., Kozlov D.V. Statistical and spatial variability of climate data in the Mareb-Gash river basin in Eritrea. *Vestnik MGSU* [[Monthly Journal on Construction and Architecture]. 2020; 151(1):85-99. DOI: 10.22227/1997-0935.2020.1.85-99 (rus.).

40. Bashar K.E. Gash river flash floods challenges to Kassala town: Mitigation and risk management. *Sudan Eng. Soc. J.* 2011; 57(1).

41. Elhassan E.S.E., Ibrahim A.M., Ibrahim Abdalla A. Flood Modeling Water Appraisal and Land Reclamation: A Case Study of Gash River. *SUST J. Eng. Comput. Sci.* 2015; 16(3):37-45.

42. Auerbach D.A., Easton Z.M., Walter M.T., Flecker A.S., Fuka D.R. Evaluating weather observations and the Climate Forecast System Reanalysis as inputs for hydrologic modelling in the tropics. *Hydrological Processes*. 2016; 30(19):3466-3477. DOI: 10.1002/hyp.10860

43. Dile Y.T., Srinivasan R. Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin. *JAWRA Journal of the American Water Resources Association*. 2014; 50(5):1226-1241. DOI: 10.1111/jawr.12182

44. Fuka D.R., Walter M.T., Macalister C., Deegaeto A.T., Steenhuis T.S., Easton, Z.M. Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrological Processes*. 2014; 28(22):5613-5623. DOI: 10.1002/hyp.10073

45. Mahto S.S., Mishra V. Does ERA-5 outperform other reanalysis products for hydrologic applications in India? *Journal of Geophysical Research: Atmospheres*. 2019; 124(16):9423-9441. DOI: 10.1029/2019jd031155

46. Zhu Q., Xuan W., Liu L., Xu Y.P. Evaluation and hydrological application of precipitation estimates derived from PERSIANN-CDR, TRMM 3B42V7, and NCEP-CFSR over humid regions in China. *Hydrological Processes*. 2016; 30(17):3061-3083. DOI: 10.1002/hyp.10846
Anghesom A. Ghebrehiwot, Dmitry V. Kozlov

47. Madsen H., Wilson G., Ammentorp H.C. Comparison of different automated strategies for calibration of rainfall-runoff models. *Journal of Hydrology*. 2002; 261(1-4):48-59. DOI: 10.1016/s0022-1694(01)00619-9

48. Nash J.E., Sutcliffe J.V. River flow forecasting through conceptual models part I - A discussion of principles. *Journal of Hydrology*. 1970; 10(3):282-290. DOI: 10.1016/0022-1694(70)90255-6

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**Л**итература

1. McGlynn B.L., Blöschl G., Bormann H., Hurkmans R., Komma J., Nandagiri L. et al. A data acquisition framework for runoff prediction in ungauged basins // Runoff Prediction in Ungauged Basins, 2013. Pp. 29–52. DOI: 10.1017/cbo9781139235761.006

2. Wheater H., Sorooshian S., Sharma K.D. Hydrological Modelling in Arid and Semi-Arid Areas. New York: Cambridge University Press, 2008.

3. Sivapalan M., Takeuchi K., Franks S.W., Gupta V.K., Karambiri H., Lakshmi V. et al. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences // Hydrological Sciences Journal. 2003. Vol. 48. Issue 6. Pp. 857–880. DOI: 10.1623/hyis.48.6.857.51421

4. Refsgaard J.C., Abbott M.B. The Role of Distributed Hydrological Modelling in Water Resources Management. Distributed Hydrological Modelling. Water Science and Technology Library, 1996. Vol. 22. Pp. 1–16.

5. Mokoen A.M.P., Kapangaziwiri E., Kahinda J.M., Hughes D.A. ECOMAG Model: an evaluation for use in South Africa. WRC Report No. TT 555/13, 2013.

6. Kapangaziwiri E., Hughes D.A., Wagener T. Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa // Hydrological Sciences Journal. 2012. Vol. 57. Issue 5. Pp. 1000–1019. DOI: 10.1080/02626667.2012.690881

7. Hughes D.A. Three decades of hydrological modelling research in South Africa // South African Journal of Science. 2004. Vol. 100. Pp. 638–642.

8. Tegegne G., Park D.K., Kim Y. Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin // Journal of Hydrology: Regional Studies. 2017. Vol. 14. Pp. 49–66. DOI: 10.1016/j.jhregsc.2017.10.002

9. Hrachowitz M., Savenije H.H.G., Blöschl G., McDonnell J.J., Sivapalan M., Pomeroy J.W. et al. A decade of Predictions in Ungauged Basins (PUB) — a review // Hydrological Sciences Journal. 2013. Vol. 58. Issue 6. Pp. 1198–1255. DOI: 10.1080/02626667.2013.803183

10. Ghebrehiwot A.A., Kozlov D.V. Hydrological modelling for ungauged basins of arid and semiarid regions: review // Вестник МГСУ. 2019. Т. 14. № 8. С. 1023–1036. DOI: 10.22227/1997-0935.2019.8.1023-1036

11. Montanari A., Young G., Savenije H.H.G., Hughes D., Wagener T., Ren L.L. et al. “Panta Rhei — Everything Flows”: Change in hydrology and society — The IAHS Scientific Decade 2013–2022 // Hydrological Sciences Journal. 2013. Vol. 58. Issue 6. Pp. 1256–1275. DOI: 10.1080/02626667.2013.809088

12. Mount N.J., Maier H.R., Toth E., Elshorbagy A., Solomatine D., Chang F.-J. et al. Data-driven modelling approaches for socio-hydrology: Opportunities and challenges within the Panta Rhei Science Plan // Hydrological Sciences Journal. 2016. Pp. 1–17. DOI: 10.1080/02626667.2016.1159683

13. McMillan H., Montanari A., Cudennec C., Savenije H., Kreibich H., Krueger T. et al. Panta Rhei 2013–2015: global perspectives on hydrology, society and change // Hydrological Sciences Journal. 2016. Pp. 1–18. DOI: 10.1080/02626667.2016.1159308

14. Sherman L.K. Streamflow from Rainfall by Unit-Graph Method. Eng. News-Record, 1932. Vol. 108. Pp. 501–505.

15. Nash J.E. The form of the instantaneous unit hydrograph. International Association of Hydrological Sciences, 1957. Vol. 45. Issue 3. Pp. 114–121.

16. Horton R.E. The role of infiltration in the hydrologic cycle // Transactions, American Geo-
Assessment of applicability of MIKE 11-NAM hydrological module for rainfall runoff modelling in a poorly studied river basin. C. 1030–1046

Horton R.E. Analysis of runoff-plat experiments with varying infiltration-capacity // Transactions, American Geophysical Union. 1939. Vol. 20. Issue 4. P. 693. DOI: 10.1029/tr020i004p00693

Crawford N.H., Linsley R.K. The synthesis of continuous stream flow hydrographs on a digital computer. California : Tech. Rep. No. 12. 1962.

Abbott M.B., Bathurst J.C., Cunge J.A., O’Connell P.E., Rasmussen J. An introduction to the European Hydrological System — Systeme Hydrologique Européen, ‘SHE’, 1: History and philosophy of a physically-based, distributed modelling system // Journal of Hydrology. 1986. Vol. 87. Issue 1–2. Pp. 45–59. DOI: 10.1016/0022-1694(86)90114-9

Beven K.J., Kirby M.J. A physically based, variable contributing area model of basin hydrology // Journal of Hydrology. 1986. Vol. 87. Issue 1–2. Pp. 45–59. DOI: 10.1016/0022-1694(86)90114-9

Dawdy D.R., O’Donnell T. Mathematical models of catchment behaviour // Journal of the Hydraulics Division. 1965. Vol. 91. Issue 4. Pp. 123–137.

Sugawara M. The flood forecasting by a series storage type model // International Symposium on Floods and their Computation. 1967. Pp. 1–6.

Kuchment L.S. Математическое моделирование речного стока. Ленинград : Гидрометеоиздат, 1972. 191 с.

Vinogradov Yu.B. Вопросы гидрологии droughts of small water basins of Central Asia and South Kazakhstan. Ленинград : Гидрометеоиздат, 1967. 262 с.

Leavesley G.H., Lichty R.W., Troutman B.M., Saindon L.G. Precipitation-runoff modelling system: User’s manual. US Geological Survey Water-Resources Investigations Report 83-4238, Reston, 1983. P. 207.

Arnold J.G., Srinivasan R., Mutiaha R.S., Williams J.R. Large area hydrological modeling and assessment. Part I: Model development // Journal of the American Water Resources Association. 1998. Vol. 34. Issue 1. Pp. 73–89. DOI: 10.1111/j.1752-1688.1998.tb05961.x

Motovilov Yu.G., Gottschalk L., Engeland K., Belokurov A. ECOMAG -regional model of hydrological cycle. Application to the NOPEX region. Oslo : Department of Geophysics, University of Oslo P.O. Box 1022 Blindern 0315, 1999. 89 p.

Singh V.P., Woolhiser D.A. Mathematical Modeling of Watershed Hydrology // Journal of Hydrologic Engineering. 2002. Vol. 7. Issue 4. Pp. 270–292. DOI: 10.1061/(asce)1084-0699(2002)7(4)(270)

Burnash R. The NWS river forecast system-catchment modelling. Computer Models of Watershed Hydrology, Colorado : Water Resources Publications, 1995. Pp. 311–366.

Sugawara M. et al. Tank model and its application to Bird Creek, Wollombi Brook, Bikin River, Kitsu River, Sanaga River and Nam Mune. Research Note of the National Research Center for Disaster Prevention, 1974. Pp. 1–64.

Bergstrom S. The HBV model. Computer Models in Watershed Modeling, Colorado: Water Resources Publications, 1995. Pp. 443–476.

Nielsen S.A., Hansen E. Numerical simulation of the rainfall-runoff process on a daily basis // Hydrology Research. 1973. Vol. 4. Issue 3. Pp. 171–190. DOI: 10.2166/nh.1973.0013

Havmo K., Madsen M.N., Dorge J. MIKE-11 a generalized river modelling package. Computer Models of Watershed Hydrology, Colorado: Water Resources Publications, 1995. Pp. 733–782.

Refsgaard J.C., Knuudsen J. Operational validation and intercomparison of different types of hydrological models // Water Resources Research. 1996. Vol. 32. Issue 7. Pp. 2189–2202. DOI: 10.1029/96wr00896

Madsen H. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives // Journal of Hydrology. 2000. Vol. 235. Issue 3–4. Pp. 276–288. DOI: 10.1016/s0022-1694(00)00279-1

Бубер А.Л. Методические подходы к решению задач многокритериальной оптимизации для управления водными ресурсами бассейнов рек в интересах водопользователей агропромышленного комплекса (АПК). М. : Всероссийский научно-исследовательский институт гидротехники и мелиорации имени А.Н. Костякова, 2018. С. 75–89.

Kozlov D.V., Ghelbrehiwot A.A. Efficacy of digital elevation and Nash models in runoff forecast // Magazine of Civil Engineering. 2019. Vol. 87. Issue 3. Pp. 103–122. DOI: 10.18720/MCE.87.9

Gelbrehiwot A., Kozlov D. GIUH-Nash based runoff prediction for Debarwa catchment in Eritrea // E3S Web of Conferences. 2019. Vol. 97. P. 05001. DOI: 10.1051/e3sconf/20199705001

Гебрехиуто А.А., Козлов Д.В. Статистическая и пространственная изменчивость климатических данных в бассейне реки Мареб-Гаш в Эритрее // Вестник МГСУ. 2020. Т. 15. № 1. С. 85–99. DOI: 10.22227/1997-0935.2020.1.85-99

Bashar K.E. Gash river flash floods challenges to Kassala town: Mitigation and risk management // Sudan Eng. Soc. J. 2011. Vol. 57. Issue 1.

Elhassan E.S.E., Ibrahim A.M., Ibrahim Abdalla A. Flood Modeling Water Appraisal and Land Reclamation: A Case Study of Gash River // SUST J. Eng. Comput. Sci. 2015. Vol. 16. Issue 3. Pp. 37–45.

Auerbach D.A., Easton Z.M., Walter M.T., Flecker A.S., Fuka D.R. Evaluating weather observations and the Climate Forecast System Reanalysis as inputs for hydrologic modelling in the tropics // Hydrological Processes. 2016. Vol. 30. Issue 19. Pp. 3466–3477. DOI: 10.1002/hyp.10860

Dile Y.T., Srinivasan R. Evaluation of CFSR climate data for hydrologic prediction in data-scarce
watersheds: an application in the Blue Nile River Basin // JAWRA Journal of the American Water Resources Association. 2014. Vol. 50. Issue 5. Pp. 1226–1241. DOI: 10.1111/jawr.12182

44. Fuka D.R., Walter M.T., Macalister C., De-gaetano A.T., Steenhuis T.S., Easton, Z.M. Using the Climate Forecast System Reanalysis as weather input data for watershed models // Hydrological Processes. 2014. Vol. 28. Issue 22. Pp. 5613–5623. DOI: 10.1002/hyp.10073

45. Mahto S.S., Mishra V. Does ERA-5 outperform other reanalysis products for hydrologic applications in India? // Journal of Geophysical Research: Atmospheres. 2019. Vol. 124. Issue 16. Pp. 9423–9441. DOI: 10.1029/2019jd031155

46. Zhu Q., Xuan W., Liu L., Xu Y.P. Evaluation and hydrological application of precipitation estimates derived from PERSIANN-CDR, TRMM 3B42V7, and NCEP-CFSR over humid regions in China // Hydrological Processes. 2016. Vol. 30. Issue 17. Pp. 3061–3083. DOI: 10.1002/hyp.10846

47. Madsen H., Wilson G., Ammentorp H.C. Comparison of different automated strategies for calibration of rainfall-runoff models // Journal of Hydrology. 2002. Vol. 261. Issue 1–4. Pp. 48–59. DOI: 10.1016/s0022-1694(01)00619-9

48. Nash J.E., Sutcliffe J.V. River flow forecasting through conceptual models part I - A discussion of principles // Journal of Hydrology. 1970. Vol. 10. Issue 3. Pp. 282–290. DOI: 10.1016/0022-1694(70)90255-6

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