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Hydrological modelling for ungauged basins of arid and semi-arid regions: review

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ABSTRACT
Introduction: hydrological modelling is a powerful tool for water resources planning, development, design, operation, and management in a catchment. It becomes more important when it is applied to areas that suffer from inadequate hydrological field data. The existing methods which are appropriate for predictions in ungauged basins include extrapolation from gauged to ungauged basins, remote sensing-based measurements, process-based hydrological models, and application of combined meteorological–hydrological models without the need to specify precipitation inputs. Nonetheless, numerous works indicate that these methods have had limitations when it comes to predictions from ungauged basins.
Materials and methods: the methods employed in this work include a detailed review of related materials on the historical development, significance, classification, selection, and recent developments of hydrological modelling in ungauged basins with an emphasis on arid and semi-arid regions.
Results: the review indicates that the development of comprehensive and effective approaches that address the unique characteristics of arid and semi-arid regions in general and similar areas within developing countries, in particular, are yet to be developed.
Conclusions: in the absence of reliable hydrometeorological data, the best approach to streamflow predictions from ungauged basins and the considered catchment would be intercomparison of two or more hydrological models. The models accommodate global, regional, and local data (if any).

KEYWORDS: a system, model, hydrological modelling, Predictions in Ungauged Basins (PUB), arid and semi-arid regions, Panta Rhei, streamflow

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Гидрологическое моделирование в условиях неизученных водосборов аридных и полуаридных регионов

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АННОТАЦИЯ
Введение: гидрологическое моделирование является мощным инструментом для организации планирования, эксплуатации и управления водными ресурсами в речном бассейне. Это особенно важно для неизученных или малоизученных с гидрологической точки зрения водосборов. Существующие подходы включают метод гидрологической аналогии и географической интерполяции, гидрологические модели с распределенными параметрами, построенные на основе комплексного использования данных дистанционного зондирования и наземных наблюдений, и с сосредоточенными параметрами, а также комбинированные метеорологические и гидрологические модели. Многочисленные литературные источники указывают на то, что эти подходы имеют ряд ограничений для их использования в условиях неизученных или малоизученных водосборов.
Материалы и методы: применены следующие методы: подробный обзор релевантных материалов по историческому развитию, значению, классификации, выбору и последним разработкам в области гидрологического моделирования в неизмеряемых бассейнах с приданием особого значения засушливым и полупустынным районам.
Результаты: выявлено, что комплексные и эффективные подходы, которые бы исследовали уникальные характеристики засушливых и полупустынных районов вообще и подобных районов в развивающихся странах, в частности, еще только предстоит разработать.

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Выводы: в отсутствие надежных гидрометеорологических данных наилучшим подходом к прогнозированию стоков из неизмеряемых бассейнов с учетом водосбора было бы взаимное сравнение двух или более гидрологических моделей. Эти модели включают глобальные, региональные и локальные данные (при наличии таковых).

КЛЮЧЕВЫЕ СЛОВА: система, модель, гидрологическое моделирование, прогнозы в условиях неизученных водосборов, аридные и полуаридные регионы, Панта Рей, речной сток

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INTRODUCTION

A system is "an aggregate or assemblage of parts, being either objects or concepts, united by some form of regular interaction or interdependence" [1]. It can be composed of several of subsystems, each of which can have a distinct input and output connection. As such, the hydrologic cycle can be represented by a system called the hydrologic system. Most hydrologic systems are extremely complex that cannot be understood in detail [1, 2]. This complexity, along with the limitations of available hydrological measurement techniques [2] thereupon inadequacy of hydrological data, leads to the modelling of hydrological processes. The data deficiencies are aggravated by the increasing effects of human activities on the components of hydrological processes (e.g., [3, 4]). Thus, in the study of complex objects such as river basins, modelling becomes an inevitable process in activities related to the study of hydrological phenomena.

"The general term modelling means replacing an object under consideration by a quasi-object, or model, to draw information about the object from the model"[1]. It is a simplified representation of a real-world system, and it consists of a set of simultaneous equations or a coherent set of operations contained within a computer program [1] that give the possibility to simulate and forecast the behaviour of a complex object [3, 5]. Similarly, hydrological models are simplified as conceptual representations of the various components of the hydrological cycle using mathematical representations of the processes associated with the transformation of climatic factors through surface and underground transport of water and energy into hydrological factors [6].

Advances in computer technology have contributed significantly to the application of hydrological models in addressing environmental and water resource issues [7]. Hydrologic modelling is required for watershed planning, development, design, operation and management concerning floods, droughts, water quality and other economic and environmental aspects (e.g., [1–3, 8–10]). Despite the widespread and long-standing use of hydrological modelling, almost all modelling tools have been developed mainly for use in sufficiently boreal areas[1] [3] with the exception of few that got international recognition; for example, agricultural catchments research unit (ACRU) and Pitman models developed in South Africa[1] [10]. Arid and semi-arid areas that possess distinctive salient features and challenges have been given little attention [3]. As noted by various researchers (e.g., [3, 6, 11, 13]), there are still water management problems that these models are not able to solve with sufficient confidence. On the other hand, a model developed specifically for boreal suggests that the model set up would possibly be boreal. As a result, it is impossible to use such models without fundamentally compromising their internal conceptual integrity [9].

Conspicuously, arid and semi-arid regions are characterized by limited water resources, severe and increasing pressure on the water body due to expanding populations and increasing water demand for various uses. Widespread pollution as a result of increasing agricultural industrial and domestic wastes, overexploitation of groundwater, climate change provide a major threat to those limited water resources (e.g., [3, 8]). Some areas are experiencing infrequent but extremely damaging floods, and other areas experience recurrent droughts causing unprecedented damage to the environment and the fragile ecosystems. Application of excessive irrigation water to various types of lands is also a key issue in water resources of arid and semi-arid regions. Those types of land include land with poor or non-existing drainage facilities, land degradation and soil erosion that leads to the loss of valuable topsoil and causes silting, sedimentation, turbidity problems and pollution in downstream areas and aquatic ecosys-

[1] WMO. Guide to hydrological practices: management of water resources and application of hydrological practices, 6th ed. Geneva: World Meteorological Organization, 2009.

tems [8]. Besides, the existing hydrological methods [3, 12], have been inadequate to produce predictions with acceptable accuracies from ungauged basins. These facts justify the need for improved models and new insights that provide appropriate responses to the problems mentioned above with the use of effective water management and appropriate decision support systems.

Since the beginning of the 21st century, the hydrologic community has been taking bold and promising collective initiatives to tackle hydrological problems with a particular emphasis on predictions in ungauged basins. The International Association of Hydrological Scientists (IAHS) Decade on Predictions in Ungauged Basins (PUB) 2003–2012 came into effect with two primary goals [13]. The first one was to improve the ability of existent hydrological models. The second one was to develop new and innovative models representing the space-time variability of hydrological processes and thereby improve the confidence in predictions in ungauged basins. To that end, it was imperative to bring the scientific community together to use PUB initiative to promote the collective understanding in hydrology towards achieving significant advances in making hydrological predictions in ungauged basins. The achieved progress was the outcome of this global initiative over the Decade on PUB [14, 14]. Following the end of the PUB initiative and underpinning and emphasizing the importance of change has led to the on-going hydrological science decade 2013–2022 of IAHS, entitled “Panta Rhei – Everything Flows” [15]. Generally, this initiative focuses on research activities on change in hydrology and society.

In light of the above background information, the objective of this work is to provide a short synopsis of historical development, classification, selection, currently used models and reflect on new developments and challenges of hydrological models with an emphasis on arid and semi-arid systems. Eventually, based on the review information in conjunction with available reference information systems, feasible hydrological modelling approaches in the interest of streamflow predictions for Upper Mereb (UM) sub-basin in Eritrea would be suggested thereby putting a solid foundation for future hydrological modeling based research activities in the area.

METHODS AND MATERIALS

Water resources and hydrological related research activities are related to hydrological modelling. Thus, complete knowledge and understanding of hydrological modelling fundamentals and processes is the first step that should be undertaken by any researcher in the field of hydrology. Therefore, from achieving the mentioned objectives, the maximum effort has been put in to review hydrological modelling advancement since its emergence, which is presented in the ensuing subsections.

Historical background of hydrologic modelling

The origin of hydrological modelling dates back to the rational method developed in the middle of the 19th century followed by single event-based models; for instance, unit hydrograph [16] and instantaneous unit hydrograph [17, 18], theory of infiltration and overland flow [19], Soil Conservation Service[2], etc. With the advancement of computing technology, hydrologic models for continuous simulation of rainfall-runoff processes emerged in the 1960s, enabling a better physical explanation and interpretation of catchment response. The most well-known of the early models is the Stanford Watershed Model (SWM) [20, 22]. Physically-based hydrological models were developed in the 1970s and 1980s to model the whole hydrologic cycle. The European Hydrological System (SHE) [23] and topography based model (TOPMODEL) [24] can serve as examples. Simultaneously, a number of somewhat less comprehensive models, for example, Hydrologic Engineering Center (HEC) [25] and semi-distributed tank model [25] were established. In Russia, considerable generalization on the development of modelling of hydrological processes in river basins (the monograph of Kuchment [26]) were some among others. It included the complete experiences of modelling of a generalized and deterministic hydrological model “Hydrograph” [27]. Simultaneously, numerous mathematical models were established for simulation of watershed hydrology and environmental and ecosystems management [7].

Other watershed hydrology models followed the developments mentioned earlier; for example, Precipitation-Runoff Modelling System (PRMS) [28], Soil Water Assessment Tool (SWAT) [29], ECOlogical Model for Applied Geophysics (ECOMAG) [30]. There has been a consistent improvement of these and other models over time. Presently, global climate models can to represent the global hydrological cycle with simplified physics-based models. In parallel, recent developments in computer power provide the ability to use increasingly powerful methods for the analysis of model performance and to specify the uncertainty associated with hydrological simulations. Despite these positive modelling advancements accuracy and availability of input data, ungauged basins, and coupling of models, which are associated to lack of scientific-hydrological understanding and technological constraint, remain to be the primary modelling challenges (e.g., [9]). Con-

[2] SCS. Supplement A, Section 4, Chapter 10, Hydrology in National engineering handbook, Washington, D.C: USDA, 1956.

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cerning Eritrean experience, credible sources of information could not be obtained.

Modelling as a mathematical tool

While the physics of the processes occurring in river basins all over the planet is practically the same, catchment areas differ in their natural conditions such as climatic, morphometric, hydrological, and geological. That may change during modelling depending on the selected water body. As described in the preceding sections, a mathematical model, like other types of models, expresses the system behaviour by a set of equations, perhaps together with logical statements expressing relationships between variables and parameters. The concept of the mathematical modelling of hydrological systems can be understood in a enormous-sense as the use of mathematics to describe features of hydrological processes. Hence, "every use of a mathematical equation to represent links between hydrological variables, or to mimic a temporal or spatial structure of a single variable, can be called mathematical modelling"[1]. It includes time series analysis and stochastic modelling, where the emphasis is on reproducing the statistical characteristics of a hydrological time series of a hydrological variable.

Modelling as a mathematical tool allows us to explore the processes occurring in the natural environment, including the water environment. Thus, mathematical models of watershed hydrology have now become accepted tools for water resources planning, development, design, operation, and management [7]. They have the advantage of resolving applied hydrological problems. The examples are computation of runoff hydrographs from gauged small watersheds and prediction and prevention of the consequences of changes in river flow under the influence of various external (e.g., climate change) and internal causes (e.g., changes in catchment characteristics) in the interests of water security, water management and development of catchments [9].

Classification of hydrologic modelling

A system could be well understood through perceptualization [2] that includes interaction, observation, and experiment. The purpose for which a built model determines its structure [7]. Thus, the knowledge of the structure of model along with perceptualization of a system helps modelers to classify hydrologic models. All hydrological models are simplified representations of the real world. Models can be either physical (e.g., laboratory-scale models), electrical analogue or mathematical. In the past, the first two models (physical and analogue) had been prevalent. However, "the mathematical model is by far the most easily and universally applicable, the most widespread and the one with the most rapid development with regard to scientific basis and application" [9]. Hydrologic mathematical models can be variously classified (e.g., [1, 7, 8, 31]) including: (i) physical, empirical or conceptual; (ii) concentrated or distributed (semi-distributed); (iii) deterministic or stochastic; (iv) linear or non-linear; (v) static or dynamic, etc. The hydrological simulation models are generally classified into deterministic and stochastic [32], as shown in Fig. 1.

Stochastic models are systems whose behaviours are governed by laws of probability [1] or if a set of

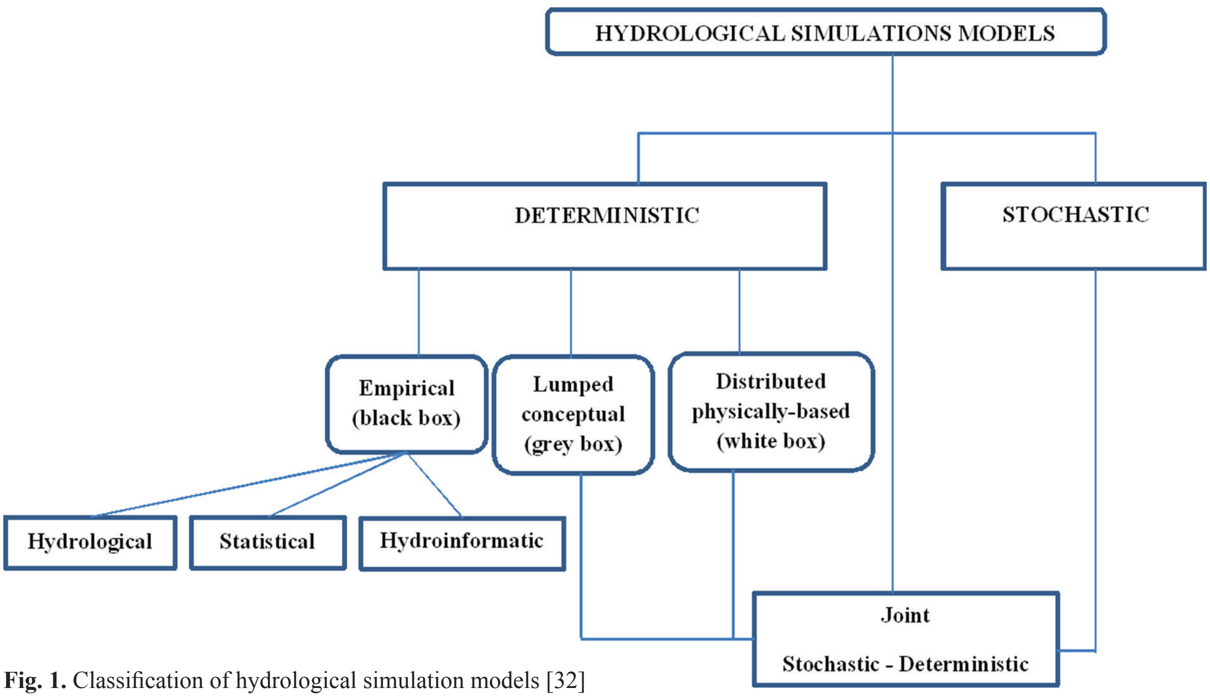

Fig. 1. Classification of hydrological simulation models [32]

input values need not produce the same output values because of the random components [3]. During the last couple of decades, stochastic modelling has gained tremendous importance because hydrological variables like rainfall, streamflows, lake levels, etc. are inherently primarily stochastic. The two main reasons for stochasticity in hydrological processes are non-uniformity of atmosphere and catchment in time and space. Though the processes are time-dependent and chance dependent, yet there remains some deterministic component also in the process. Hence, stochastic modelling primarily includes time series analysis of the process. Commonly used techniques in stochastic modelling are regression, transfer functions, neural networks (data-driven), and system identification.

Deterministic models uniquely define their outputs (for instance streamflow) for specified input (for instance rainfall) and initial boundary conditions. Deterministic, physically-based models are based on the known physical laws of science such asthe laws of conservation of mass and energy, taking into account the specific conditions of the problem, the properties and internal relations of the investigated water body, studying the real processes to obtain the output response of the system. There are several classes of them: dynamic (conceptual) flow models with concentrated parameters, physical and mathematical models (using equations of mathematical physics to describe hydrological processes) with semi-distributed and distributed parameters.

Deterministic models could be event-based or continuous simulation models. An event-based model produces output only for specific periods, whereas a continuous model produces the continuous output [3]. Event-based models usually require small time steps (e.g., second). These models are suitable for analysing the influence of design storms. The more significant time steps (e.g., days) are usually sufficient for continuous models that are appropriate for long-term assessment of hydrological and land-use change and watershed management practices [33].

In lumped models, the entire river basin is taken as one unit where spatial variability is omitted. In such a modelling approach input data are related to system outputs without considering the spatial processes, patterns, and organization of the characteristics governing the processes, for example, Stanford Watershed Model [21]. The lumped models have two limitations; (1) it considers a large number of assumptions, and (2) they only simulate the streamflow just at the watershed outlet. While the former hinders the applications of lumped models especially to large watersheds, the latter, however, does not allow estimating the flow at some interior locations in a river basin for engineering design, flood forecasting and studying the effects of land use or climate change. Thus, lumped models fail to represent the interaction of surface and subsurface processes fully. Due to some of the difficulties caused by this method, numerous complex lumped rainfall-runoff models have been developed and documented [2, 33].

A distributed model accounts for spatial variations of variables and parameters [31] , thereby explicit characterization of the processes and patterns is made; for example, SWM and SHE based on the commercial versions of the Danish MIKE-SHE [34] and the English SHETRAN [35]. The model system developed at the Institute of water problems of RAS (Kuchment et al. 1986), and received its continuation, including in the physico-mathematical model ECOMAG [30], as well as the model “Hydrograph” developed by Vinogradov [27] at the State Hydrological Institute (Saint Petersburg). Recent works of Motovilov [30] is devoted to the development of deterministic models of river flow formation, belonging to the class of physical and mathematical models with semi-distributed and distributed parameters. The main problem of physical and mathematical models is reduced to the following idea. The equations of mathematical physics inadequately describe some hydrological processes. They are also applied in real catchments for unusual spatial scales, where the parameters of models cannot be measured, and they need to be calibrated in the same way as it is done in conceptual models of river flow.

The advantages of a distributed model [31] are the possibility of considering spatially variable inputs and outputs, assessment of pollutants and sediment transport, and also analysing the hydrological response at ungauged basins. The availability of high spatial resolution data such as digital elevation model (DEM), precipitation, vegetation, soil, and other atmospheric variables has led to the development of many sophisticated distributed hydrologic models. However, the application of the distributed models mainly associated with parameterization, calibration, and error correction have been some of the major challenges to modellers. “The more complexity means the more parameters; the more parameters mean the more calibration problems; the more calibration problems often mean the more uncertainty in the predictions, particularly outside the range of the calibration data” [2]. The primary sources of uncertainty are considered to be the estimation of the excessive parameters within distributed models. Most of the studies on distributed modelling can be divided into two categories in regard to parameterization [36]; homogeneity and heterogeneity. The first class uses calibration techniques to find optimal values for the rest of the parameters whereas the latter uses soil and vegetation data to physically estimate the value of the parameters based on watershed characteristics within all the hydrologic units. Calibration in the second approach is not easy; it is an intense, time consuming, and inefficient procedure due to the number of parameters involved.

Deterministic models can also be classified according to whether the model gives a lumped or a distributed description of the area under consideration, and whether the description of the hydrological processes is empirical, conceptual, or more physically-based. As most conceptual models are also lumped, and as most physically-based models are also distributed, the three main groups of deterministic models emerge [32]. These groups are (i) empirically hydrological methods, (ii) statistically based methods, and (iii) hydroinformatics based methods. Probably, the best known among the empirically hydrological models in hydrology is the unit hydrograph [16] model. Statistically based methods are often mathematically more advanced than the empirical hydrological methods (e.g., regression and correlation models such as autoregressive integrated moving average, (ARIMA). Meanwhile, hydroinformatics based models are introduced in the last couple of decades based on neural networks and evolutionary algorithms. Various researchers have reported that the empirical hydrological models represent an unambiguous relationship between the hydraulic (e.g., flow volume) and morphometric characteristics of a riverbed.

The joint stochastic-deterministic models are composed of two, in principle, equally essential parts, namely a deterministic core within a stochastic frame [8, 37]. Despite the widely reported application of deterministic models in rainfall-runoff modelling, the distinction between stochastic and deterministic models remains unclear.The reason is that there are examples of models which add a stochastic error model to the deterministic predictions and vice versa [2]. However, the rule of thumb to distinguish between stochastic and deterministic [2] is that if the model output variables are associated with some variance or other measures of predictive dispersion, the model can be considered stochastic. At the same time, if the output values are single-valued at any time step, the model can be considered deterministic. The practical experience of some hydrologists and modellers [6] showed a successful application of dynamic-stochastic models.

Hydrologic model selection

The selection of a model remains part of the art of hydrological modelling on account of objective methods of choosing the best model have not been developed. Later, various literature[1] (e.g., [7]) reported that apart from the three studies on intercomparison of watershed hydrology models conducted under the umbrella of World Meteorological Organization (WMO) and limited efforts to compare on component processes, comprehensive comparisons of watershed hydrology models are yet to be done. A decade later, [2] said that model selection is still a daunting task to make a decision on the choice of a model for a particular problem from the available models in the literature (e.g., [2, 9]). Therefore, the assertion of relative advantages and disadvantages of models proposed for operational use are often not easy.

The selection of a model suitable for a specific hydrological situation has implications in water resources development, and management, hydrological forecasting and in planning for further research in modelling[1]. The researchers have outlined various methodologies for the use of hydrologic models for prediction (e.g., [1, 2 38]). Almost all these methodologies involved in model selection generally consider nearly the same factors and criteria. Those include the objective of the model, type of system and hydrological element to be modelled, climatic and physiographical characteristics of the watershed, data availability, model simplicity, possible homogeneity of catchments, and ability of the model to be updated conveniently based on current hydrological and meteorological conditions.

A model structure appropriate for the perceived modelling purpose, the given catchment characteristics and data has to be selected. The modelling purpose addresses the modelling time step and the issues pertaining to which hydrological processes need to be considered [38]. As far as selection of a model is concerned, numerous works (e.g., [2, 10]) indicate that application of a single watershed model does not often fulfil all the conditions of a study. Depending on the environment under which a model has been developed, it may include a combination of two or more model (e.g., lumped and distributed) parameter components as discussed in the preceding sections. Also, some components of the model may be empirical, while others are physically-based. The linkage of two or more watershed models [33] may result in a modelling environment that provides more distributed parameter physically-based components leading to a provision of better handling of heterogeneity of watershed parameters and a better explanation of the physical processes used in the modelling approach.

Proper understanding of the principle of parsimony that captures the key response modes of the hydrological system may also contribute towards appropriate model selection. This principle is based on the concept "what can happen through fewer principles happens in vain through more" [39]. It requires models to have the most straightforward parameterization that can be used to represent the data. Parsimonious model structures have reduced problems of identifiability since only model parameters justified by the data are kept [38]. The approach of retaining only the necessary components ensures that the model components used are positively affirmed. On the contrary, it is worth noting that using this principle in the context of rainfall-runoff modelling may not guarantee that all necessary model components are identified. Therefore, careful attention ought to be paid so that the model does not omit important hydrologic processes for a particular problem.

Recent developments: state of the art

According to K.J. Beven [2], researchers have developed many interesting research methods since the start of the PUB initiative of IAHS. The implementation of the Representative Elementary Watershed (REW) concept, the improvement of land surface parameterisations as boundary conditions for atmospheric circulation models, the widespread use of distributed conceptual models encouraged by the freely available software (e.g., SWAT), developments in data assimilation for forecasting, the greater understanding of problems of uncertainty in model calibration and validation, and other advances [15] are some among others. Moreover, understanding and underlining the importance of change has led to the emergence of the on-going hydrological science decade — Panta Rhei [15].

M. Hrachowitz [13] and Blöschl [14] broadly discuss some of the findings obtained during the PUB Decade 2003–2012. These findingsrevealed the presence of global changes in spatiotemporal temperature and precipitation patterns, regional and local changes in river flow and hydrochemical regimes. The combined effects of climate change, land-use changes and long-term dynamics intrinsic to the hydro-climatic system probably drove these changes. One of the major causes of predictive uncertainty has been reported to be unreliable climate projections and incomplete process understanding [13]. These challenges, together with the majority of basins worldwide being ungauged, were increasingly undermining the resilience of human society to water-related hazards [13]; flood, quantity, and quality of water supply and drought.

To overcome these challenges, the International Association of Hydrological Sciences (IAHS) launched the PUB initiative in 2003 [4]. Its goal was "to formulate and implement appropriate science programmes which engage and energise the scientific community, in a coordinated and effective manner, towards achieving major advances in the capacity to make hydrological predictions in ungauged basins." This strategy was a principle paradigm shift in scientific hydrology, from the method of empiricism into physical processes and system understanding [14]. Apart from unifying the hydrologic community, PUB's achievements include advances in process understanding, flexible approaches to modelling, models as tools, the need for uncertainty assessment and comparative hydrology are some among others.

Despite the successes of PUB initiative, some challenges are yet to be addressed [13]; for example, lack of achieving robust and reliable predictions, lack of harmonization of modelling strategies and failure to ensure sustainable water resources management strategies. Specifically, Hrachowitz and others [13] concluded that the vast majority of the successes have been in gauged rather than in ungauged basins, which has negative implications for developing countries. Failure to come up with appropriate methods of predictions in such regions is linked to the absence of capacity to make reliable predictions that hamper sustainable water resources management and the development and effective flood and drought mitigation strategies. Moreover, some reports that indicate the declining of hydrometeorological monitoring networks not only in the developing world but also in developed countries due to social, economic and political changes (e.g., [13–15]).

The on-going scientific decade of IAHS 2013–2022 is entitled with Panta Rhei "Everything Flows" — Change in hydrology and society. It is an initiative to adopt an interdisciplinary approach to address problems that can only be solved through community efforts at all levels. Panta Rhei initiative believes "hydrological systems are the interface between the environment and human needs for water, and understanding hydrological change is the key to planning sustainable water exploitation and managing water supply for drinking, sanitation, food, energy, and for societal development". In spite of its ambitious intention of transforming the conventional hydrologic modelling into socio-hydrologic modeling [40], the study on the global perspectives of the Panta Rhei [41] concluded that many challenges associated with understanding and predicting change in hydrology and society hamper it. Those challenges also empower communities to mitigate and adapt to those changes.

Remote sensing is a primary source of observations of land surface hydrological fluxes and state variables, particularly in regions where in-situ networks are sparse. A combination of remote sensing data and advanced data processing, archiving, and visualization technologies greatly assist in resolving hydrological problems. The ease of access to these useful sources of information and processing tools has significantly advanced hydrologic studies. Nonetheless, obtaining useful hydrological information from this wealth of data has never been easy [2]. The global data-based broad-scale assessment provides a starting point for localized assessment at low cost. However, it is worth reporting that such data neither include internal catchment characteristics that can influence runoff dynamics nor shorter-term climate and weather information that lead to dynamic hydrology and storm runoff [14]. Regional data sources of varying availability and accuracy provide more detailed information at a higher cost over smaller scales. Finally, local observations may provide a detailed understanding of the catchment response at the local scale [13].

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The predictive context varies vastly around the world due to differences in processes, data availability, modellers' experience, and purpose of the prediction. Therefore, there is no single best method developed for all situations so far [2, 8, 38]. In contrast, the particular circumstances one finds can be exploited to develop creative methods for runoff predictions using proxy data. PUB recommends practical approaches for predicting runoff in ungauged basins through knowledge accumulation which is connected to reading the landscape, understanding the runoff signatures and processes, process similarity and grouping, the use of an appropriate model, hydrological interpretation, and uncertainties.

As has been pointed out earlier, several data collection approaches may be available (global, regional, or local) that may maximize the information obtained from the available data sources. However, there is no substitute for a stream gauge installation. In the absence of a stream gauging station, it would be better to think of alternative strategies that consider catchment runoff characteristics [14]. Runoff prediction performance is strongly related to runoff data availability, and performance is lower in data-poor regions [14]. Methods appropriate for ungauged basins include extrapolation of response information from gauged to ungauged basins, measurements by remote sensing, application of process-based hydrological models where the climate inputs are specified or are measured, and application of combined meteorological and hydrological models without the need to specify precipitation inputs. Finally, although not fully global, an extensive database is available (e.g., Global Runoff Data Base (GRDB)) at the Global Runoff Data Center (GRDC).

RESULTS

The extensive hydrological modelling review in the preceding section should boil down to regional and local levels. Accordingly, an attempt has been made to explore and assess the existing hydrological modelling practices and challenges in arid and semi-arid regions with an emphasis on the East African region, where the UM sub-basin is situated.

Despite the critical importance of water in arid and semi-arid areas, hydrological data have historically been severely limited. Since a long time back, this constraint, along with the lack of high-quality observations, has been the major limitations of the development of arid and semi-arid hydrology. Various case studies carried out in the East African region under the auspices of the Global Water Partnership (GWP)[3] show that there are two most critical challenges identified in all case studies. The first one is the lack of systematic and reliable data collection, and the second one is management to enable information to be shared and disseminated to support evidence-based decision-making and planning. Possible reasons are that the populations are usually sparse and limited economic resources, harsh climate, and infrequent hydrological events. Moreover, the political and socio-economic history of the East African region has not been conducive to the collection and maintenance of hydrological records. For example, rainfall and stream gauging stations in Eritrea started during the last 19^{th} and early 20^{th} centuries. However, in many cases, war, inadequate economic resources, and shifting social and political priorities have meant that these networks have not been maintained and in some cases, the historical data are not readily accessible [42]. The absence of long-term and reliable hydrological data in Eritrea has been causing major challenges in water resources development and management [42]. Subsequently, there has been a tendency to depend on humid-area experience and modelling tools and data from other regions. Such approaches do not only yield inaccurate results but also leads to adopting inappropriate management solutions which ignore the specific features of dry land response [3].

The climate in the East Africa region is rather complicated. Likewise, Eritrea's hydrology is characterized by a high degree of variability with agro-ecological zones varying from humid and moist highlands to extremely arid lowlands. Within individual zones, hydrological (rainfall and streamflow) and meteorological (temperature, radiation, humidity, etc.) variability is high. Extremes of floods and droughts and components of hydrological and meteorological variability cause some of the greatest challenges to sustainable water-resource management [43]. Water resource utilization and land-use changes likely to impact on natural hydrological processes are also not well documented in many areas. Due to the lack of water laws and regulations, the amounts of water abstracted for different purposes are highly temporally variable and unknown [43]. As such, calibration and validation of hydrological model results against historical data, even where they exist, becomes a difficult task. Under such circumstances, the selection of a suitable hydrologic model would be an uphill task. At this point, there is limited credible information on the models that have been employed in Eritrea in general and in Mereb-Gash river basin in particular. Single event-based model GIUH-Nash [42, 44] and distributed model - SWAT are the limited available literature on the existing models in and near the UM catchment.

The Mereb-Gash is one of the five major river basins in Eritrea. It is an ephemeral river having a main-channel length of 489 km and a catchment area of 21.805 km^2 up to the outlet near the town of Tessenei. It

[3] Global Water Partnership, Integrated Water Resource Management in East Africa. 2015.

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has the availability of limited discharge data but likely to have the highest potential for agricultural activities, both for rain-fed and irrigated, among the other river basins. Average annual discharge for the Mereb-Gash at Kassala (Sudan) over the years 1907–1929 was 430 Mm^3. Unlike the Setit River, which originates in Ethiopia and also forms a natural boundary with Eritrea, the waters of the Mereb do not usually reach the Nile but are lost in the sands of the Eastern plains of Sudan. The Mereb-Gash is dry for much of the year, but like the Setit River, it is subjected to sudden floods during the rainy season. According to Alemngus A., Amlesom S., Bovas L.J.J. [43], about 82 % of the area of Mereb-Gash basin lies within Eritrea and the remaining in Ethiopia.

The upper reaches of Mereb-Gash rise to the south-west of Asmara - the capital city of Eritrea. The river originates North of Emba-Taqera in Central Eritrea. The Upper Mereb (UM) catchment which is a subbasin of the Mereb-Gash river basin, with its outlet at Ghergera, is located in the southern region, an administrative subzone of Debarwa. Specifically, the outlet at Ghergera is 38°55’22” E and 15°00’17” N. It has a drainage area of about 525 km^2. According to the agro-ecological classification of Eritrea, the UM lies in moist highlands zone where temperature varies from 0 to 32 °C and an average annual rainfall of around 547 mm. The climate in the catchment can be characterized as moderate with December–January being the coldest and March-April the hottest. Maximum precipitation occurs in the summer season, specifically in July and August with a monthly mean rainfall of 185 mm and 175 mm, respectively.

Frequently, the type of model is dictated by the availability of data as has been described before. In general, distributed models require more data than lumped models. In most cases, needed data either do not exist or are not available in full. That is one reason why regionalization and synthetic techniques are useful. Even if the needed data are available, problems remain with regard to the completeness, inaccuracy, and inhomogeneity of data [7]. In respect of this, there is limited available hydrological and meteorological data for UM: 3 years hourly and daily rainfall, 15 years monthly rainfall, 12 years average daily flow with the exception of 3 years missing data and 2 years of water level information. Recently, two major multi-purpose dams (Adi-Halo and Ghergera) were built in the UM catchment. These dams will likely affect the hydrological processes of the area under consideration.

Extensive studies on the comparative assessment of predictions in PUB [45, 46] show that runoff hydrograph, flood, and low flows predictions tend to be “more accurate in humid than in arid catchments and more accurate in large than in small catchments”. Moreover, it was found out that spatial proximity and similarity methods perform best in humid catchments while in arid catchments similarity and parameter regression methods perform slightly better. The multi-criteria based model comparison in Ethiopia [11] shows that the performance of the models for reproducing observed streamflow was as a function of the watershed size. The simple conceptual models performed best in smaller watersheds for reproducing observed streamflow, whereas complex model performed best for the largest watershed leading to the conclusion that the distributed models are suitable for complex watersheds on account of their physical heterogeneities.

Considering the available information about the catchment where hydrologic modelling is to be applied, it would be impractical to think of getting acceptable results from a single model. Instead, the application of two or more models of different or the same classes would be compulsory; for example, Nash model (lumped) for single event-based hydrograph predictions, SWAT or MIKE (distributed) for continuous streamflow simulations. While the limited observed rainfall and streamflow data could be used for calibration and verification of the selected models, the hydrometeorological data obtained from the global, regional and local sources, which are likely to be extracted from remote sensing technology-based databases, for model simulation.

CONCLUSIONS

Hydrological modelling has a long history of development and application in the areas of water resources and the environment. The multitudes of literature in the field of hydrology reveal that hydrologic modelling has continually evolved over the years. Irrespective of the presence of various hydrological modelling classification methodologies, the purpose remains the same; watershed planning, development, design, operation, assessment, and management for floods, droughts, water quality and addressing other environmental aspects. However, almost all modelling tools have been mainly developed for boreal applications exceptfor few models developed for arid and semi-arid areas that got international recognition.

The traditional and existing hydrological methods have been insufficient to provide predictions with reasonable accuracies from ungauged basins. Subsequently, collective professional efforts have been attempted to overcome these issues such as the IAHS Decade on PUB, Panta Rhei, and implementation of REW concept, etc. These global initiatives backed by the freely available distributed models (e.g., SWAT), increased data extraction and processing techniques through the application of remote sensing and geographic information system. Also, high computational capacity of computers

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has been contributing towards extensive application and advancement of hydrological modelling.

PUB-based studies show the presence of global changes in spatiotemporal temperature and precipitation patterns, regional and local changes in river flow and hydrochemical regimes as a result of the combined effects of climate change, land-use changes and long-term dynamics intrinsic to the hydro-climatic system. Moreover, one of the major causes of predictive uncertainty has been reported to be unreliable climate projections and incomplete process understanding. Despite these promising achievements, it is worthy to note that the vast majority of the successes of the PUB and other initiatives have been limited to gauged basins. As such, challenges linked to the lack of appropriate predictions in ungauged basins in arid and semi-arid regions are yet to be addressed. Such challenges could only be met by the concerted and joint efforts of hydrologists and affected societies around the world.

Finally, the selection of a model, especially for predictions in ungauged basins requires special consideration. The authors realized that there is no single best model for predictions under various circumstances. Thus, on the basis of the review and inadequacy of the available reference information of the UM catchment, it is concluded that the best approach to predictions of streamflow would be intercomparison of two or more models that use global, regional and local data (if any).

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