A methodological framework for the hydrological model selection process in water resource management projects

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Abstract
This study aims to present a process for hydrological model exploration for selecting an appropriate model compatible with the modeling objectives. The process consists of three stages: (1) initial choice based on the modeling objectives; (2) model selection based on intercomparison among underlying conceptualizations of the models; and (3) final model selection based on influencing criteria such as availability of the model software and documentation, and availability of appropriate data. As an applied example, the process was used to find an appropriate model for a project to evaluate water supply and demand under climate and land use change scenarios in the Gorgan-rud River Basin, Iran. The criteria affecting the final choice of a hydrological model were classified into three categories: (1) criteria related to the model, (2) criteria related to the model user, and (3) criteria related to the study area.

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Recommendations for resource managers

- It is vital to simulate the hydrological conditions on an appropriate temporal and spatial scale useful for management purposes.
- The simulation resolution should be consistent with the resource management requirements.
- The simulation resolution depends on modeling objectives.
- The criteria related to data availability, the model user and those related to the study area are among the main factors affecting the final choice of a hydrological model.

KEYWORDS

classification of hydrological models, hydrological model choice, hydrological modeling, the Gorgan-rud River Basin, water resources project

1 INTRODUCTION

Models are simple representations of the real world (Sorooshian et al., 2008) and are increasingly used to support natural resources management (Jakeman et al., 2006). Hydrological models have been developed to describe the nonlinear and dynamic transformation of precipitation into runoff through processes such as surface and subsurface flows, infiltration, interception, evaporation, transpiration, snowmelt, and so on (Kour et al., 2016). Such models comprise a set of equations used to estimate the runoff as a function of various parameters used to express the watershed characteristics (Devi et al., 2015) such as geography, geology, and land use (Jajarmizadeh et al., 2012).

The increase in available computing power has had an important role in the development of models. While event-based models were developed in the 1930s, the first hydrological models for continuous simulation of rainfall-runoff processes emerged in the 1960s, when computing power was sufficient to represent the relevant land phase processes in a simplified “conceptual” manner. Later, in the 1970s and 1980s, it was possible to develop “physically based” hydrological models through solving a coupled set of partial differential equations to represent overland, in-stream, and subsurface flows and transport processes, as well as evaporation from land and water surfaces (Wheater et al., 1993, 2007). Therefore, there are many hydrological models ranging from lumped models such as the unit hydrograph concept (e.g. Croke and Jakeman, 2004) to very complicated distributed models such as MIKE SHE (Kalin & Hantush, 2003). This makes difficulty for hydrologic modelers to determine which model is best to apply in a catchment for a particular modeling exercise (Marshall et al., 2005). It means that it is not a straightforward step for hydrological modelers to select a suitable model complexity level
for a particular purpose (Wheater et al., 1993). No model can be considered as ideal for a range of hydrological conditions and catchments. Beside the importance of the acceptable performance of the model in a particular application, user preferences and their ability to use a particular model, the aim of the modeling, and the available time to develop and execute a model must be considered (Marshall et al., 2005).

Kauffeldt et al. (2016) explored large-scale hydrological models and evaluated their suitability for flood prediction. In their study, the accessibility of the models and the model compatibility with a specific purpose was emphasized and the importance of describing the hydrological processes in each model was also pointed out.

Tilford et al. (2007) presented a structured method for selecting the most appropriate model to apply in a specific situation. They considered economic, operational, and other considerations beside technical factors such as catchment characteristics. They also considered the extensive use of checklists, flow charts, risk assessment matrices, and other techniques to guide users through the decision making process of model selection.

To achieve the goal of the CFCAS Project, Cunderlik (2003) reviewed and compared existing hydrological models and information to select an appropriate model that can be used as the most suitable hydrologic modeling tool for the project. A large number of hydrological models were studied and eighteen models were selected based on four criteria including: “important output required for the project,” “hydrological processes that are needed to obtain the desired output,” “availability of input data,” and “cost.” In the next step, the selected 18 models were then ranked based on several evaluation criteria reflecting specific project requirements. At the second level, total ranks attributed to the 18 selected models work as an objective measure for determining the most appropriate model(s).

The correct choice of a model for use in a specific project should lead to better results. The aim of this study is to present a model choice process for use in water projects and to provide an applied example in the Gorgan-rud River Basin located in Iran based on the presented model choice process. The results of this study may be helpful for water researchers in decision-making around choosing the appropriate hydrological model to use in water projects. Also, exploring the hydrological models considered here in terms of the effective characteristics in decision-making can be an available database to facilitate and accelerate future model choices.

2 MATERIALS AND METHODS

2.1 Hydrological model selection process

In this study the hydrological model selection process was presented as three stages including: (1) initial selection based on modeling purpose; (2) selection of the model based on inter-comparison; and (3) final selection of the model based on influencing criteria. To find appropriate model(s) to use and execute in a specific project, model screening is undertaken based on the presented process. The three stages of the presented process are explained below. Figure 1 also shows the methodological framework used for selecting a suitable hydrological model.
2.1.1 First stage: Initial selection based on modeling purpose

In the first stage of the choice of a hydrological model, defining the purpose of the modeling is critical and the initial choice is made based on the different classification of models (Beven, 2011). We have to consider how much detail we need to know, which processes and components are needed, and whether our research is result-oriented or hydrologic-knowledge-oriented? As shown in Figure 1, answers to these questions can be useful in determining the appropriate class of models. If the modeling purpose is only to predict flow discharge and the calibration data are available, then simple lumped models such as IHACRES can provide predictions that are as good, if not better, than complex physically based models (Jakeman and Hornberger, 1993; Beven, 2011). When the research is result-oriented a parsimonious model, which has simplicity and explanatory predictive power together, is preferred. Therefore, it is evident that the reasons for modeling should have a significant influence on choosing a model family or families to represent the system (Jakeman et al., 2006). Some explanations about...
different classes of hydrological models are available below. More information especially about dendritic classification of the hydrological models is given in Jajarmizadeh et al. (2012).

- **Deterministic versus Stochastic models**
  Regarding their mathematical structure, hydrological models are divided into two categories: deterministic and stochastic (Shaw, 1983). The underlying assumptions of determinism are based on cause and effect relationships with known inputs/parameters, so a deterministic model produces numerical outputs. The underlying assumption of stochasticity is that model inputs and parameters are distributions rather than numbers, with the distributions representing variability (e.g., spatial heterogeneity) and uncertainty in the values. Therefore, through the use of the cause and effect relationships, a stochastic model produces distributions as the model output. Hence, in a stochastic model, statistical patterns of a particular phenomenon are used to simulate the effect of that phenomenon (Obropta & Kardos, 2007; Yevjevieh, 1987). It should be noted that there is not a clear difference between these two types of models (Beven, 2011; Obropta & Kardos, 2007) and, as a working rule, if the output values of the model are single-valued at any time step, that model can be considered a deterministic model, without considering the nature of the underlying computations (Beven, 2011).

- **Black-box (Empirical) versus Gray-box (Conceptual) versus White-box (Physically based) models**
  Empirical or black-box models (Jakeman et al., 2006) are those in which runoff is directly derived from rainfall data without explicit consideration of the processes involved in the transformation of rainfall to runoff. Different forms of these empirical models include regression to data mining techniques from the field of artificial intelligence (neural networks, support vector machines, classification and regression trees, and fuzzy inference) (Beven, 2011). In contrast, physically based, white-box, or theory-based (Jakeman et al., 2006) models are those in which the processes and factors affecting the studied phenomenon are known. These types of models are a mathematically idealized representation of the real phenomenon and are also called mechanistic models that involve the principles of physical processes (Beven, 2011; Devi et al., 2015). This type of modeling is mostly deductive, but we cannot avoid some empiricism when describing the hydrological processes and estimating the model parameters (Beven, 2011). Gray-box, parametric, conceptual, or theory-influenced empirical types (Jakeman et al., 2006) are located between the two modes of white-box and black-box in which the processes of rainfall to runoff transformation are known to some extent. These models include semi-empirical equations with a physical base (Devi et al., 2015).

- **Lumped versus Semi-distributed versus Distributed models**
  Lumped models consider the watershed as a unit described by, usually, up to a few tens of parameters and variables (Refsgaard, 1997) and the parameters describing the watershed, hydrological processes, input data, or boundary conditions do not consider spatial variability across the watershed (noting that uniformity across the catchment is not assumed). The processes are represented either by differential equations based on hydrologic and hydraulic principles or by empirical equations (Bengtson & Padmanabhan, 1999). In comparison, distributed hydrological models are designed to take into account the spatial characteristics of the watershed. In this type of model, the watershed is divided into many grid cells with each cell described using several parameters and variables. Often the total number of parameters in distributed models is reduced by making assumptions about the spatial
distribution of the values of the parameters (e.g., related to a spatial data set linked to soil properties, land cover, etc.). The difference between the number of parameters in lumped and distributed models dictates different requirements in terms of determining the parameters, calibration, and validation for lumped and distributed models (Refsgaard, 1997). In semi-distributed models, the whole of the watershed is divided into a collection of sub-watersheds (Devi et al., 2015) or hydrologic response units (e.g., England & Onstad, 1968) with each unit being modeled using a lumped approach, and diffuse flux between neighboring units is ignored.

- **Event-based versus Continuous models**
  Based on the temporal scale at which the model is used, hydrological models are divided into two categories: event-based and continuous (contiguous). Event-based modeling of a watershed defines the hydrological processes at the temporal scale of an event, simulating the watershed responses to a particular rainfall event. For continuous modeling, hydrological processes and phenomena are simulated over a longer time period (Chu & Steinman, 2009).

- **Newtonian and Darwinian approaches in developing hydrological models**
  Hydrological models can also be divided into “Newtonian” (Physics-like) and “Darwinian” (Ecology-like) approaches (Harman & Troch, 2014; Sivapalan et al., 2011; Wang & Tang, 2014). In the Newtonian approach, hydrological behavior is inferred from the universal laws (Sivapalan et al., 2011) such as Newton’s law of motion, especially the momentum equation and other conservation equations, namely mass and energy (Wang & Tang, 2014). In the Newtonian approach, the developed hydrological model is a mechanistic characterization of the hydrological processes and their combined components including initial conditions, boundary conditions, and the parameters of the model (Sivapalan et al., 2011; Wang & Tang, 2014). The Soil and Water Assessment Tool (SWAT) model may be considered an example of a Newtonian (and semi-distributed) model (Malagò et al., 2018). In comparison, the Darwinian approach studies the patterns of variation in hydrological behavior within a population of watersheds as seen in observations (Harman & Troch, 2014; Wang & Tang, 2014) and postulates a theory for relating the observed patterns (similarities and variations) to the processes believed responsible for creating those patterns (Wang & Tang, 2014). This approach is based on empirical data from a large number of watersheds (Malagò et al., 2018). The Budyko curve is among the most well-known Darwinian models used for long-term or climatological water balance generation at the watershed scale (Malagò et al., 2018; Wang & Tang, 2014). In general, Top-Down (Holism) and Bottom-Up (Reductionist) approaches are used for the development of models (Savenije, 2009; Sivapalan et al., 2003), generally using the Darwinian and Newtonian methods, respectively (Mianabadi et al., 2017). The Top-Down approach in hydrological modeling can be defined as the attempt to predict the overall response of the watershed and its functioning based on an interpretation of the observed response at the watershed scale (Sivapalan et al., 2003). The Bottom-Up approach in hydrological modeling is the attempt to predict the overall response of the watershed based on the process knowledge gained at smaller temporal and spatial scales and then scaling-up small-scale understanding of models to the watershed scale (Sivapalan et al., 2003).

### 2.1.2 Second stage: Selection of the model based on intercomparison

Intercomparison can reveal the strengths and weaknesses of each model (Wheater et al., 1993) which can be achieved using the short ladder (shallow evaluation) and long ladder (deep
evaluation) approaches (Bahremand, 2016). In the short ladder approach, the performance of the models is compared based on the simulated hydrographs generated by each model being considered, and the observed data. In the long ladder approach, evaluation enables us to know which hydrological processes are represented in the model and how they are interlinked. So, in this type of assessment, it is not reasonable to compare an artificial neural network black-box model with a fully distributed physically based model (Bahremand, 2016). To reach the final choice of model, the candidate models are compared with each other using the long ladder approach. In this regard, the procedure adapted from Beven (2011) can be helpful by listing: (1) the models of interest; (2) the variables simulated and predicted by each model; (3) assumptions considered in each model; (4) the inputs of each model; and then (5) weighing the conditions/limitations, and (6) determining if any model satisfies all conditions.

2.1.3 | Third stage: Final selection of the model based on influencing criteria

Furthermore, issues that can be effective in the final choice of a hydrological model for a specific project can include the availability of time and money for the model user (Beven, 2011); the availability of the model, code, and documentation for public use; the temporal and spatial scale of the model; the existence of multiple applications of the model in different regions; the climatic conditions for which a specific model has been developed; and the quantity and quality of the available climatic and hydrologic data.

2.2 | The example application

The model selection framework presented in this study has been put into practice using an example watershed. The framework is applied to find a suitable hydrological model to use in a project related to water resources, with the main aim of assessing the water supply and demand in the Gorgan-rud River Basin under climate change and land use change scenarios. The Gorgan-rud River Basin is one of the north-east basins of Iran with an area about 11,260 km² and is located to the south-east of the Caspian Sea in folds to the north of the Alborz Mountains (Sheikh et al., 2009; Varvani et al., 2002). There are three dams constructed in the basin, namely Boustan, Golestan, and Voshmgir (see Figure 2). One part of the Gorgan-rud River Basin is covered with forest and the other is without forest cover (Varvani et al., 2002). In terms of population, the Basin is important for the Golestan Province in Iran, hosting approximately 1.2 million people. The Basin supports an economy based on agriculture (46% of population), industry and mining (20% of population), and supports wildlife habitats (Azari et al., 2017).

2.2.1 | First stage: Initial model selection based on modeling purpose

The vast area of the Basin and the existence of multiple land uses such as forest, agriculture, rangeland, residential areas, bare lands, as well as dams and natural water bodies contribute to the hydrologic complexity of the region and generate constraints for choosing a suitable model to simulate the hydrological components. Furthermore, in considering the aim of the project (exploring the Basin’s supply and demand balance under climate and land use scenarios), the
selected hydrological model should be able to simulate groundwater recharge as well as runoff, infiltration, and evapotranspiration. As physically based hydrological models are more complete in this regard, we selected them for more exploration. Again, based on the aim of the project, the future longer-term water supply and demand balance will be explored, so event-based hydrological models are not suitable for use in the project, and thus it is necessary to invoke continuous hydrological models. At the first stage of hydrological model screening, 24 distributed and semidistributed hydrological models were considered. It should be noted that two models of HEC-HMS and SWMM are used in both event-based and continuous forms, so the continuous version of these two models was also considered.

2.2.2 Second stage: Selection of the model based on intercomparison

Initially, a list of the models was created (Tables 1 and 2) and then 26 distributed and semidistributed hydrological models were selected based on the first stage of the model choice. These included (1) ANSWERS-2000, (2) ArcEGMO&ArcEGMO-URBAN, (3) CEQUEAU, (4) COSERO (5) DH SVM, (6) GBHM, (7) HBV, (8) HSPF, (9) HydroBEAM, (10) HYDROTEL, (11) INCA, (12) IWFM, (13) LISFLOOD, (14) MESH, (15) MIKE SHE, (16) OWLS, (17) SHETRAN, (18) SLURP, (19) SWAT, (20) SWM, (21) TOPKAPI, (22) TOPMODEL, (23) VIC, (24) WaSiM, (25) WATFLOOD, (26) WetSpa and WetSpa-Python and also the continuous version of the HEC-HMS and SWMM models. These models were then compared and some of those models were rejected for the reasons given in Table 3.
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | References |
|----|----------------|-----------|----------|-----------------------|--------|--------------------------|------------|
| 1  | P. Y. Julien   | Cascade 2 Dimensional model | CASC2D   | Physically based, distributed, event-based | Rainfall and runoff data; DEM, Soil, and land use maps | Runoff simulation using Hortonian mechanism, simulation of hydrological impacts of land use/land cover in a watershed | Julien and Saghafian (1991); Liu and De Smedt (2004); Marsik and Waylen (2006); |
| 2  | Deva K. Borah  | Dynamic Watershed Simulation model | DWSM     | Physically based, distributed, event-based | Climatic and hydrologic data; topography, soil, and land use maps | Surface and subsurface flow simulation; propagation of flood waves; soil erosion, and entrainment and transport of sediment and chemicals (nonpoint-source pollutants) | Borah et al. (2007); Gao et al. (2013) |
| 3  | United States Army Corps of Engineers | Hydrologic Engineering Center-Hydrologic Modeling System | HEC-HMS  | Physically based, conceptual, semidistributed, event-based, and continuous | Physical characteristics of the watershed; rainfall and runoff data | Runoff simulation, routing, capable of considering a reservoir, simulation of groundwater recharge | Nourali et al. (2016) |
| 4  | Institute for Global Change Research | Institute for Hydrosphere-Atmospheric Sciences | IHAS     | Spatial scale: The maximum is 10,000 km² for a grid; temporal scale: 1 h | Daily routine meteorological data | This is a combined model which is composed of a simple SVAT (Soil-Vegetation-Atmosphere Transfer) model, runoff model and river routing model explain snowmelt, evapotranspiration, thawing and freezing of permafrost and river flow | http://hydrologicmodels.tamu.edu/ models.htm |

(Continues)
| No | Model developer                                      | Full name                  | Acronyms  | Model characteristics                          | Inputs                                                                 | Outputs and applications                                                                 | References                                      |
|----|------------------------------------------------------|----------------------------|-----------|-----------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------------------------|
| 5  | United State Department of Agriculture & agricultural research service | Kinematic Runoff and Erosion | KINEROS2  | Physically based, semidistributed, event-based | Rainfall and runoff data; DEM, soil, and land use maps                  | Simulation of runoff, sediment, and infiltration                                       | Goodric et al. (2012); Memarian et al. (2016) |
| 6  | Center for Ecological Modelling, IMAR - Lisbon University | Modelo de ErosãoFísico e DISTRIBUIDO | MEFIDIS   | Physically based, distributed, event-based   | Maps of altimetry, flow direction, soil, land cover, channels (optional), and humidity index (optional) | Net runoff generation, net soil losses                                                  | http://hydrologicmodels.tamu.edu/models.htm     |
| 7  | United States Environmental Protection Agency         | Storm Water Management Model | SWMM      | Physically based, distributed, event-based and continuous | Hourly or more data of precipitation, daily evaporation, subwatershed area, percent of impervious area, storage loss, slope, and also hydraulic and water quality data | Water quantity, water quality, flow routing, mainly for use in urban and suburban areas | Khaleghi et al. (2020) http://hydrologicmodels.tamu.edu/models.htm |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
| 1  | Bouraoui and Dillaha (1996) | Areal Nonpoint Source Watershed Environment Response Simulation | ANSWERS-2000 | Physically based, distributed, continuous | Maps of topography, soil, land use; rainfall, temperature, and solar radiation | Qualitative evaluation of the management measures regarding the runoff, and sediment, nitrogen, and phosphor losses in agricultural watersheds; simulation of interception, surface storage, infiltration, percolation, sediment detachment and transport, nitrogen and phosphor dynamics, nitrate and ammonium losses | Bouraoui and Dillaha (1996); Migliaccio and Srivastava (2007); http://ww2.bse.vt.edu/ANSWERS/History.php |
| 2  | Bureau of Applied Hydrology, Germany | ArcEGMO & ArcEGMO-URBAN | | Deterministic, conceptual, physically based, distributed, and continuous | Maps of elevation, slope, aspect, land use, groundwater depth; time | Simulation of runoff, water balance, nitrogen and carbon balance, | http://hydrologicmodels.tamu.edu/models.htm; Biegel et al. (2005) |

(Continues)
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
|    |                 |           |          |                       |        | vegetation modeling,     |           |
|    |                 |           |          |                       |        | studying the climate    |           |
|    |                 |           |          |                       |        | change and land use      |           |
|    |                 |           |          |                       |        | change impacts,          |           |
|    |                 |           |          |                       |        | for urban watersheds     |           |
| 3  | Guy Morin       | –         | CEQUEAU  | Process-based,        | Minimum and maximum temperature, liquid and solid precipitation, runoff, Physiographic data | Flow simulation, short-term and long-term prediction, horizontally and vertically simulation of water flow | Morin et al. (1998); http://ete.inrs.ca/ete/publications/cequeau-hydrological-model; http://www1.ete.inrs.ca/activites/modeles/cequeau/aindex.html |
|    |                 |           |          | deterministic,        |        |                          |           |
|    |                 |           |          | distributed,         |        |                          |           |
|    |                 |           |          | continuous           |        |                          |           |
| 4  | University of Natural Resources and Life Sciences, Vienna (Austria) | Continuous Semidistributed Runoff | COSERO | Conceptual, deterministic, semidistributed, continuous | Temperature, precipitation, potential evapotranspiration, | The possibility for link to the other models such as reservoir simulation models, for studying climate change impacts, temporal scales of monthly, daily, hourly, and less, with the | Kling et al. (2015) |
| No | Model developer       | Full name                          | Acronyms | Model characteristics                                                                 | Inputs                                                                 | Outputs and applications                                                                                                           | Reference                                                                                                                                 |
|----|-----------------------|------------------------------------|----------|---------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| 5  | Wigmosta et al. (1994)| Distributed Hydrology Soil Vegetation | DHSVM    | Physically based, distributed, continuous, spatial scale with 30 m to 150 m resolution and daily and less temporal scale | DEM, information of vegetation, soil, stream channel distribution      | Streamflow prediction in regional scale, dynamic representation of soil moisture distribution, snow cover, evapotranspiration, and runoff | Wigmosta et al. (2002); Saeed et al. (2009); http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM |
| 6  | Geomorphology-Based Hydrology Model | GBHM    | Physically based, distributed, continuous | DEM, soil, and land use maps; temperature, precipitation; relative humidity; sunny hours; and wind velocity | Flow simulation                                                             |                                                                                                                                     | Wang et al. (2015); http://hydro.iis.u-tokyo.ac.jp/%7Ehhexg/Model/Model_GBHM.html                                                      |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
| 7  | Swedish Meteorological and Hydrological Institute | Hydrologiska ByransVattenbalansavdelning | HBV | Conceptual, process-based, distributed/semidistributed, continuous | Precipitation, temperature, (daily) discharge, (daily and monthly) potential evapotranspiration | Overflow design, flood simulation, water resources evaluation | Bergstrom (1976); Yaghoubi and Massah Bavani (2014) |
| 8  | Bicknell et al. (1993) | Hydrological Simulation Program FORTRAN | HSPF | Distributed, continuous | Potential precipitation and evapotranspiration, air temperature, dew point temperature, solar radiation for snowmelt, soil surface characteristics such as land use pattern and land management measures, soil type, drainage density, topography | Simulation of hydrological and hydraulic processes and water quality | Donigian et al. (1995); Singh and Woolhiser (2002); Al-Abed and Al-Sharif (2008); Zhang et al. (2009) |
| 9  | Water Resources Research Center, Hydrological River Basin | | HydroBEAM | Air pressure, air temperature, | Water quantity calculation, | | |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|-------|--------------------------|-----------|
| 10 | Jean-Pierre Fortin et al. | HYDROTEL | Physically based, distributed, continuous | Hydro-climatic data including precipitation and temperature data; streamflow; DEM, land use and soil texture maps; full drainage structure of the watershed | Flow simulation for each reach of the river in watershed; simulation of the spatial distribution of hydrological variables, simulation of hydrological processes including climatic data, snow accumulation and snowmelt data, evapotranspiration, vertical | Fortin et al. (1991); Fortin et al. (2001); Khalili et al. (2011); https://archive.codeplex.com/?p=hydrotel |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
| 11 | Jakeman & Hornberger (1993) | Identification of unit Hydrograph And Component flows from Rainfall, Evaporation, and Streamflow data | IHACRES | hybrid conceptual- metric, continuous; spatial scale: small experimental watersheds to basins; temporal scale: minute, daily, monthly | The characteristics of watershed; precipitation and flow data | With two linear and non-linear modules; for studying the impact of land use and climate change; the ability to consider the storage | Croke and Jakeman (2008); Jamali et al. (2013) [https://toolkit.ewater.org.au/tools/IHACRES](https://toolkit.ewater.org.au/tools/IHACRES) |
| 12 | Model development as a part of EU2 projects | Integrated Catchment Model | INCA | Process-based and dynamic; semidistributed | Daily climatic data including precipitation, effective precipitation, soil moisture deficit, and data related to water quality and sediment | Simulation of hydrological flow path in surface water and groundwater systems and routing the dissolved materials and pollutants in daily time step | Whitehead et al. (2015); [http://www.reading.ac.uk/ geographyandenvironmentalscience/research/INCA/ges-INCA.aspx](http://www.reading.ac.uk/ geographyandenvironmentalscience/research/INCA/ges-INCA.aspx) |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
| 13 | Bay-Delta Office, California Department of Water Resources | Integrated Water Flow Model | IWFM | Physically based, Continuous | Required data are different based on the purpose | Simulation of surface flow, groundwater flow, the interaction between groundwater and stream; considering the storage; the model was developed for large-scale agricultural areas | Scherberg (2012); http://baydeltaoffice.water.ca.gov/modelling/hydrology/IWFM |
| 14 | floods group of the Natural Hazards Project of the Joint Research Centre (JRC) of the European Commission | Physically based River Basin Modelling System | LISFLOOD | Physically based, Continuous, distributed, usually daily and hourly scale | Topography, soil, and land use maps; climatic and hydrologic data | Flow simulation and channel routing, simulation of water balance in watershed in daily time scale, simulation of hydrological processes including snowmelt, infiltration, interception, evaporation, | Van Der Knijff et al. (2010) |
| No | Model developer         | Full name | Acronyms | Model characteristics | Inputs                                                                 | Outputs and applications                                                                 | Reference                                      |
|----|-------------------------|-----------|----------|-----------------------|----------------------------------------------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------|
| 15 | Canada’s Environment    | Environment Community Surface Hydrological model | MESH      | Distributed, Physically based | Precipitation, temperature, barometric pressure, wind velocity, longwave radiation, shortwave radiation, geographical information | Simulation of vertical balance of water and energy | http://www.usask.ca/ip3/models1/mesh.htm; MacLean (2009); MacLean et al. (2010) |
| 16 | Danish Hydraulic Institute (DHI) | System Hydrologique Europeen (SHE) | MIKE SHE   | Deterministic, physically based | Topography map, characteristics of geological layers, Surface water and groundwater interactions | Liu et al. (2016)                            |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
|    |                |           |          | distributed, continuous | cross-sections and length of the channel, climatic data (daily precipitation, mean daily temperature, potential evapotranspiration), water table, groundwater table, groundwater extraction, saturated hydraulic conductivity, soil moisture storage curve, land use, cropping pattern, leaf area index, and root depth | channel flow, unsaturated zone flow, groundwater flow, and the outputs including real evapotranspiration, river flow, recharge of the saturated zone, soil content in unsaturated zone, flow interaction between river and aquifer, rivers and drainage areas, rivers and surface flow. | [http://hydrologicmodels.tamu.edu/models.htm](http://hydrologicmodels.tamu.edu/models.htm) |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|-----------------|-----------|----------|------------------------|--------|-------------------------|-----------|
| 17 | Wilson Huaisheng Chen | Object Watershed Link Simulation | OWLS | Physically based, distributed, continuous, three dimensional | DEM, precipitation, temperature, and data related to soil, geographic coordinates. | Streamflow, water storage, vertical flow, soil moisture content, temperature; suitable for mountainous watersheds | Chen (1996) http://www.hydromodel.com |
| 18 | Hydrologic System (SHE) | System Hydrologique Europeen Transport | SHETRAN | Physically based, distributed, continuous | Climatic and hydrologic data including precipitation, evaporation, discharge; DEM, land use and soil maps; satellite images | Simulation of water quantity and quality | Ewen et al. (2000); Liu and De Smedt (2004) |
| 19 | Kite (1995) | Semidistributed Land Use-based Runoff Processes | SLURP | Process-based, semidistributed | Daily climatic data | Simulation of vertical water balance in each element of the subbasin/land cover matrix; considering the impacts of reservoirs, water | Kite (2001) |
| No | Model developer | Full name | Acronyms | Model characteristics | Inputs | Outputs and applications | Reference |
|----|----------------|-----------|----------|-----------------------|--------|--------------------------|-----------|
| 20 | Agricultural Researches Service (ARS) | Soil and Water Assessment Tool | SWAT | Physically based, semidistributed | Topographic, land use, and soil maps; precipitation; minimum and maximum temperature | Rainfall-runoff simulation; water quality (Nitrogen and Phosphor); erosion simulation; considering the storage unit | Liu et al. (2016); Ghabadi et al. (2015); Singh and Woolhiser (2002); |
| 21 | Stanford University | Stanford Watershed Model | SWM | Conceptual | DEM; precipitation; soil and land use maps | Runoff simulation | Singh and Woolhiser (2002) |
| 22 | Environmental Studies & Earth Sciences, University of Bologna | TOPographic Kinematic Approximation and Integration | TOPKAPI | Physically based, Fully distributed | DEM; precipitation; soil map; land use map | Simulation of infiltration excess overland flow; saturated overland flow; subsurface flow; evapotranspiration; channel routing; surface | http://www.progea.net/ prodotti.php?p= TOPKAPI&lin= inglese http://hydrologicmodels.tamu.edu/ models.htm |

(Continues)
| No | Model developer           | Full name                        | Acronyms | Model characteristics          | Inputs                                                                 | Outputs and applications                                                                 | Reference                                                                                           |
|----|---------------------------|----------------------------------|----------|--------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| 23 | Beven & Kirkby (1979)     | Physically Based Runoff Production Model | TOPMODEL | Physically based, semidistributed, continuous | Precipitation; discharge; topographic information                     | Runoff simulation                                                                                   | Beven and Freer (2001); Nourani and Mano (2007); https://csdms.colorado.edu/wiki/Model:TOPMODEL |
| 24 | Xu Liang                  | Variable Infiltration Capacity    | VIC      | Physically based; semidistributed | Time series of daily climatic data (precipitation, temperature, wind velocity, radiation) | Runoff simulation, for studying the impacts of climate change and land use change on water, for use in cold climate, simulation of base flow and infiltration, considering the storage | Liang et al. (1994); http://vic.readthedocs.io/en/master                                      |
| No | Model developer       | Full name                                      | Acronyms         | Model characteristics                                                                 | Inputs                                      | Outputs and applications                                                                 | Reference                                      |
|----|-----------------------|-----------------------------------------------|------------------|---------------------------------------------------------------------------------------|---------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------|
| 25 | Jorg Schulla          | Water Flow and Balance Simulation Model       | WaSiM            | Physically based; deterministic; distributed; continuous                              | Land use map; DEM; elevation; soil map      | For studying the impact on river basins; runoff prediction, groundwater recharge, soil water; the ability for considering dam | Schulla (2019); http://www.wasim.ch/en/index.html |
| 26 | Waterloo University   | WATFLOOD                                      |                  | Process-based; semidistributed; continuous; in the watershed scale                    | Land use map; DEM; soil map; precipitation and discharge data | Flow prediction; flood studies; for studying the climate change impacts; for studying the environmental impacts; considering the storage | León et al. (1999); Kouwen (2018)              |
| 27 | Vrije U. Brussels (VUB) | Water and Energy Transfer between Soil, Plants and Atmosphere | WetSpa&WetSpa Python | Physically based; distributed; continuous                                             | Topographic map; land use map; soil texture; climatic data (daily and hourly) | Flow hydrograph; spatial distribution of the hydrological characteristics including soil moisture, infiltration rate, groundwater recharge, runoff | Wang et al. (1996); Bahremand et al. (2021) |
TABLE 3  Hydrological models rejected in the second screening stage

| No | Model                          | Reason(s) for rejecting the model                                      |
|----|--------------------------------|------------------------------------------------------------------------|
| 1  | ANSWERS-2000                   | The concentration of the model is on water quality, for application in the agricultural watersheds |
| 2  | ArcEGMO&ArcEGMO-URBAN           | For application in the urban watersheds                                 |
| 3  | COSERO                         | Not able to simulate the recharge                                      |
| 4  | HBV                            | The main output of the model is discharge                               |
| 5  | HydroBEAM                      | Does not consider the reservoir                                        |
| 6  | INCA                           | The concentration of the model is on water quality                      |
| 7  | IWFIM                          | The model was developed for large-scale agricultural regions            |
| 8  | OWLS                           | The model was developed for small forest watersheds, the number of parameters of the model (46 parameters) is high |
| 9  | SHETRAN                        | The model does not consider the storage                                 |
| 10 | SWAT                           | Not able to correctly simulate the recharge                             |
| 11 | SWM                            | The model does not consider the recharge                                |
| 12 | SWMM                           | For application in the urban watersheds                                 |
| 13 | TOPMODEL                       | The model consumptions are valid for small and medium watersheds       |
| 14 | TOPKAPI                        | The main aim of the model is flood simulation and therefore, it does not consider deep soil layer |
| 15 | WetSpa & WetSpa-Python         | Does not consider the reservoir                                        |

2.2.3  Third stage: Final selection of the model based on other influencing criteria

In the next step, more exploration of the remaining hydrological models was undertaken through literature review and studying the characteristics of the models based on available information. Thus, the models which could not be used in the project were rejected, leading to a final choice of hydrological models (Table 4).

3  RESULTS

Based on Sections 2.1.1 and 2.2.1 and Figure 1, initial selection of a hydrological model is made based on modeling purpose, and the appropriate class of the hydrological models is selected. Therefore, a list of models of different classes was prepared. There are two well-known black-box models used in hydrology: ANN (Solaimani, 2009) and ARIMA (Lohani et al., 2012; Mirzavand & Ghazavi, 2015). Table 1 provides some information about the event-based distributed and semi-distributed models and Table 2 provides some information about the continuous distributed, semi-distributed, and lumped models. These tables provide syntheses that facilitate passing the second stage of model selection for water researchers and managers.
Based on Sections 2.1.2 and 2.2.2 and also Figure 1, in the second stage of the hydrological model selection, the models in the preferred classes are compared and the inappropriate models are rejected. Table 3 presents the models rejected in the second stage of hydrological model selection process applied for the Gorgan-Rud River Basin. The models rejected are due to their characteristics and reflect an attempt to perform the deep (long ladder) evaluation of the models belonging to the selected class.

In the third stage of the hydrological model selection, the study area characteristics, and the limitations of the model user and the model itself are considered. Table 4 presents the results of using the hydrological model selection process for the Gorgan-Rud River Basin in the third stage. The models rejected are due to a combination of practical reasons: the limitations of the model users in the current project (e.g., MESH hydrological model needs hourly climatic and hydrological data which are not available for the study area); and reasons such as model software accessibility which are not related to model characteristics (e.g., the LISFLOOD hydrological model could be an appropriate model for the current project but software for it is not available to the public).

Finally, based on the screenings made on the hydrological models, the continuous version of HEC-HMS, namely HEC-HMS-SMA² was chosen to use in the project. It should be noted that having several successful applications of this model in Iran, plus availability of the model documentation and software were factors in the final selection of the HEC-HMS-SMA model.

| No | Model   | Reason(s) for rejecting the model                                                                 | Limiting criteria          |
|----|---------|---------------------------------------------------------------------------------------------------|---------------------------|
| 1  | CEQUEAU | Model documentation is in French                                                                 | Model user                |
| 2  | DHSVM   | It is a research model and is continuously under development. Limited efforts were made to create a user-friendly interface. Its code is available but no technical support is provided | Model user and model      |
| 3  | SLURP   | The software is provided at high price                                                              | Model user                |
| 4  | HYDROTEL| The literature of the model is limited, the information presented in the model website is limited    | Model user and model      |
| 5  | VIC     | The complexity of the model, it needs a long time to execute and parametrize, it is not executed under windows | Model and model user      |
| 6  | WaSiM   | The complexity of the model, high number of model parameters, and its application in Europe and especially in alpine watersheds | Model and study area      |
| 7  | WATFLOOD| Model concentration on flood prediction, model developers do not support the users especially students | Model and model user      |
| 8  | LISFLOOD| The software of the model is not available for public                                              | Model                      |
| 9  | MESH    | It needs climatic and hydrologic data in the hourly scale                                          | Study area                |
| 10 | MIKE SHE| Complexity of the model, the software of the model cannot be downloaded in Iran                    | Model and model user      |
| 11 | GBHM    | It needs hourly rainfall and temperature data                                                       | Study area                |
| 12 | HSPF    | Model execution under DOS and UNIX, It needs hourly rainfall and temperature data                  | Model                      |
4 | DISCUSSION AND CONCLUSIONS

The main aim of this study was to present a process for hydrological model exploration, which can be used to select an appropriate model compatible with the modeling objectives. The process consists of three stages of (1) initial choice based on the modeling objectives, (2) selection of the model based on intercomparison, and (3) final selection of the model based on influencing criteria. In the second stage, the long ladder evaluation (deep evaluation) framework can be useful, which is based on the comparison among underlying conceptualizations of the models.

In the first stage of choosing a model for a specific project, reasons for modeling should have a large influence on deciding the model family/families to represent the system. For example, if the project aims to estimate the runoff in the outlet of the watershed, a lumped model can meet the purpose, and it is not necessary to use a more complicated distributed or semi-distributed model. In this regard, common classifications of hydrological models were explored in this study. Based on the purpose of our project, namely, assessing the water supply and demand in the Gorgan-rud River Basin under climate change and land use change scenarios, we selected 26 continuous distributed and semi-distributed models along with the SWMM and HEC-HMS models which can be used for both event-based and continuous modeling purposes.

In the second stage, the intercomparison of the models was based on a comparison of the formulation of the models and the hydrological processes considered therein. Components and processes which may be needed in the hydrological modeling include, for example, those associated with snow, lakes, reservoirs, interception, infiltration, groundwater recharge, and infiltration. Therefore, consideration of the hydrological models in this regard and the investigation of the presence or absence of these components in the model are useful in choosing a suitable model. Based on the characteristics of the 28 models selected in the first stage, 15 models were rejected (Table 1). For example, ANSWERS-2000 was rejected because the focus of the model is on water quality and it has been developed for application in agricultural watersheds, whereas WetSpa and WetSpa-Python were rejected because the WetSpa hydrological model does not consider the impact of reservoirs.

The final selection of a hydrologic model for a specific project can be achieved based on other practical criteria such as the availability of time and money for model users, availability of the model software for public use, availability of the model documents, the potential for free use of the model software and codes, multiple applications of the model, the climate condition for which a specific model has been developed, and the quantity and quality of the available data about the climate, lithology, soil, land cover/land use, and hydrology. The criteria important for reaching the final choice of a hydrological model can be categorized in three classes including (1) criteria related to the model; (2) criteria related to the model user; and (3) criteria related to the study area.

In this stage of finding an appropriate model for application in the Gorgan-Rud River Basin, 12 models were rejected. For example, CEQUEAU was rejected because model documentation is in French and this is due to limitations of the model users in the current study and so can be placed in the class of criteria related to the model user. DHSVM was rejected because it is a research model and is continuously under development. Limited efforts have been made to create a user-friendly interface. Its code is available but no technical support is provided - all of these reasons belong to the class of criteria related to the model. GBHM was rejected because it requires hourly rainfall and temperature data. This time resolution is not available for the
Gorgan-Rud River Basin - this rejection pertains to the class of criteria related to the study area. Based on Table 4, eight of the reasons for rejecting the models in the third stage belong to the class of criteria related to the model, seven of them belong to criteria related to the model user, and three of them are linked to the study area.

Despite the multiplicity of the hydrological models explored and attempts made in this study to present a process for choosing a hydrological model, sometimes finding a model which can meet all needs of a particular project is a difficult process. This challenge is because each project is unique in terms of its objectives, temporal and spatial scales, the characteristics of the study area, and even limitations and abilities of the model users. Based on the results of this study, most of the reasons for model rejection in the third stage belong to criteria related to the model. Therefore, choosing a model will be an easier process for model users if the hydrologists either attempt to develop hydrological models based on the characteristics of their countries as well as compatibility with the type and availability of data, or try to localize/customize the existing hydrological models.

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Diba Ghonchepour: conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); resources (equal); visualization (equal); writing original draft (equal).
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ENDNOTES
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