Comparative study of GCMs, RCMs, downscaling and hydrological models: a review toward future climate change impact estimation

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Abstract

Water resources are naturally influenced by weather, topography, geology and environment. These factors cause difficulties in evaluating future water resources under changing climate. The Intergovernmental Panel on Climate Change (IPCC) reported that the increasing greenhouse gases which can cause sea level rise increase frequency of storms, heavy rainfall events and droughts. In order to quantify the future change of the hydrological cycle rainfall, different modeling approaches like the use of global climate models, regional climate models and hydrological models (for local scale about 200 km²) are being used. This paper aims to investigate the challenges in modeling because of different parameter or variable or model conceptualization uncertainties using different scenarios, downscaling methods and climatic variables. This work helps to quantify future water resources to maintain quality of water to support aquatic life, agriculture and industrial needs. Challenges in climate change impact analysis in the present research and knowledge gaps are also discussed.

Keywords Global climate models · Regional climate models · Hydrological models · Downscaling · Climate change impact · Ensemble models

1 Introduction

Water is essential for the survival of human beings. Water resources play an important role in the economy of a country. However, water resources are unevenly distributed spatially and temporally and they are under pressure due to anthropogenic activities and natural variability. Natural variability of water resources can be attributed to weather, topography, geology and environment. Man-made pressures on water resources are increasing mainly as a result of urbanization, population growth, growing competition for water and pollution. These changes are aggravated by climate change and variations in natural conditions. The depletion of water resources in many parts of the world is a major environmental problem of this century. Because

of human influence and natural variability, it has always been a challenge for researchers and planners to assess the water resources with minimum uncertainty under continuous perturbed climatic conditions.

Global climate changes influence hydrological and meteorological characteristics at spatial and temporal scales [66]. According to Intergovernmental Panel on Climate Change [52], climate change is not only due to natural phenomenon variability but also as a result of global warming. The changing climate with high influence of global warming has significant impact on the hydrological cycle [6], which further alters precipitation, runoff, evapotranspiration, etc., changing entire water body characteristics [67] and water quality [137]. River basins are often influenced by increasing population and

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land use patterns along with climate change. These factors are responsible for uncertainty in the hydrological response estimation. Under perturbed climatic scenario, the increasing temperature and changing rainfall patterns affect hydrological responses. The impacts of climate change are major consideration for integrated assessment of water resources. Simulation models with future projections of hydrological variables like GCM, RCM, and hydrological models are being used for future planning and management in order to combat increasing water demand and scarcity. Integration of models considers feedback between the climate and hydrological system. Another emerging field of projection of future predictions is the multi-model ensembles (MMEs) [9]. Multi-model ensembles give more reliable outputs concerning future runoff in the basins. Apart from climate change, some major factors like land use, land cover and slope along the river basins govern runoff. Evaporation plays a major role in forests along the river banks in deciding the runoff [9]. Simulation models require much advancement in order to predict regional precipitation, runoff and evaporation accurately. According to [55] report, the planets climates are expected to change in such a way that some regions are likely to experience greater amounts of precipitation, while other regions experience lower amounts of precipitation. Model selection to evaluate future climate change considers the fact that increasing greenhouse gases plays a major role. Future climate changes due to rising greenhouse gases are expected to increase both the intensity and frequency of precipitation in central India from 2070 to 2099 [93]. Several studies reveal the impact of future climate change extremes over India in terms of precipitation such as increased (floods) or scarcity (drought) or number of wet and dry days. Such extremes are expected to have serious impact on food, economy, life and property. For India, which is an agro-based country, such changes are likely to have a serious impact.

The analysis of climate impact can be categorized into the following groups:

- (a) Study of historical trends of stream flow/runoff water with seasonal variations daily/monthly/seasonally
- (b) Using general circulation models (GCMs)
- (c) Downscaling GCM output to reduce uncertainty
- (d) Suitable regional climate models
- (e) Local hydrological models

2 General circulation models

To simulate the present climate and to predict future climate change, general circulation models (GCMs) have been developed. The output data of GCM are too coarse

to use in hydrological modeling [15] directly. Instead of using single GCM, combinations of multiple GCMs [1] and scenarios reduce uncertainty associated with results [25, 122, 128]. The future climatic series are generally drawn from GCMs, which simulate global and regional climate system [53].

GCMs are considered as major source to explore complexity of climate and to give quantitative measures of future climate change [52]. As GCMs are with large grid size (grid-cell resolutions of approximately 250 and 600 km), it would be difficult to predict variations in weather variables like local variance, persistence, frequencies, topography, etc., because of which GCMs do not accurately define local phenomenon; hence, results are often downscaled to use with hydrological models to assess impacts of projected climate changes [22]. As the future climate cannot be known with certainty, climate change projections must be used to assess the possible future climate trends. Precipitation is inherently difficult to model with climate variables, as local topographic variables have greater control on precipitation occurrence. The highest source of uncertainty in climate impact [50] studies comes from differences between projections among GCMs, followed by differences among emissions scenarios [15, 76, 128]. In many studies, the source of uncertainty is calculated separately (GCMs, RCMs, downscaling methods, emission scenarios and hydrological models). Downscaling bridges the gap between GCM and fine-resolution hydrological models at local scale [104]. One-way coupling approach is useful to evaluate future changes in precipitation [98], evaporation and runoff [16], which integrates GCM scenario outputs with hydrological models through statistical downscaling methods. Using sensitivity analysis, parameters are identified which influence model validation [29] based on observed variables and weather variables at each location. Multi-model approach using mean of ensembles gives better assessment of possible future climate change.

3 Different methods of downscaling

Different methods are used to downscale the output data from GCM model to match with hydrological data and surface variables (Fig. 1). The common methods of downscaling are (1) delta/ratio methods, (2) stochastic/statistical downscaling and (3) dynamic downscaling or nested models.

While studying climate change impact, if only one downscaling method is chosen then results must be calibrated carefully. The specific drawback of each downscaling method results from climate projection scenario (Table 1).

Fig. 1 Schematics representing three possible methods to use GCM-simulated temperature for hydrological modeling: **a** direct use of GCM temperature, **b** delta-change approach and **c** scaling approach. Source: [111]

Table 1 Comparative study of statistical and dynamical downscaling techniques [125]

	Statistical downscaling	Dynamical downscaling
Advantages	<ul style="list-style-type: none"> Comparatively cheap and computationally efficient Can provide point-scale climatic variables from GCM-scale output Can be used to derive variables not available from RCMs Easily transferable to other regions Based on standard and accepted statistical procedures Able to directly incorporate observations into method 	<ul style="list-style-type: none"> Produces responses based on physically consistent processes Produces finer resolution information from GCM-scale output that can resolve atmospheric processes on a smaller scale
Disadvantages	<ul style="list-style-type: none"> Require long and reliable observed historical data series for calibration Dependent upon choice of predictors Non-stationarity in the predictor–predictand relationship Climate system feedbacks not included Dependent on GCM boundary forcing; affected by biases in underlying GCM Domain size, climatic region and season affect downscaling skill 	<ul style="list-style-type: none"> Computationally intensive Limited number of scenario ensembles available Strongly dependent on GCM boundary forcing

Precipitation and stream flow models need very fine-scale parameters from GCM downscaling [111] output data. Statistical downscaling and dynamic downscaling methods are dependent on GCM boundary forcing, domain size and location. As uncertainties can propagate through the chain of GCM, RCM, downscaling, hydrological modeling, emission scenario, it is still a major obstacle to quantify and reduce the uncertainty associated with each source [111, 112]. The hydrological responses such as stream flow [76], surface runoff and evapotranspiration change seasonally [16] with climatic change [108]. The dynamic downscaling approach cannot be directly used due to uncertainties between the grid-scale and point-scale observed data. RCM data can be corrected using downscaling method considering that present-day climate remains invariant in future climate projections [4]. GCMs' outputs are used as predictors to estimate impact of climate change on regional precipitation using a statistical downscaling method [18, 21]. The main demands on large-scale variables are:

1. Reliably simulated by GCM
2. Readily available from archives of GCMs' output
3. Strongly correlated with the surface variables of interest
4. Carry climate change information. [126]

Climate change impact on future water resource studies allows the prediction of present and future climate and estimates the future discharges in river basins [2]. A bias correction technique applied to GCM-downscaled output data helps remove bias between simulated and observed results. While predicting future climate variables [33, 76] like the winter precipitation in north India, the model produced near real-time observations [114]. Regression-based statistical downscaling methods establish a statistical relationship between GCM outcome, climate variables and local surface variables depending on the historical record. Delta method has an impact on statistical properties like mean and variance of temperature and precipitation. Sometimes, the final output is biased when corrections are made to variables [18]. Bias corrections in RCM's output before using it as input in hydrological model is recommended as RCMs are reported to have inherent systematic errors due to imperfect conceptualization. The choice of model has a significant impact on climate change response on hydrological variables [36]. Water bodies are sensitive to climate change impact as base flow is influenced by temperature and precipitation [83] which cause change in seasonal low flows and high flows [20, 135].

4 Regional climate models (RCMs)

RCM (approximately 25–50 km) is better suited for areas with complex physiographical features because of its higher resolution as compared to GCM. Growing greenhouse gases and aerosols indicate increase in precipitation and temperature by the end of the twenty-first century [99]. RCM outputs are being used for hydrological analysis like effects of climate change on ground water [118], runoff estimation, flood risk assessment, precipitation [85], global warming [4], land use–land cover change [106] and evaporation calculations. The use of RCM output is being increased due to availability of large number of models and the capability of the model to represent the local climate [33]. The RCM-projected future climate changes are further influenced by human-induced climate change at regional level, and hence it needs further investigation of results [13].

RCM predictions over India often show over estimates in Western Ghats due to dry bias [26, 86] as the atmospheric moisture is removed by the warm ocean currents.

5 Hydrological models

Hydrological models predict future changes of total water yield in a basin including stream flow/runoff using historical data of temperature and precipitation with respect to greenhouse gases, precipitation, land use and land cover. Present hydrological models are being improved according to IPCCs Vth Report based on new emission scenarios, i.e., the Representative Concentration Pathway (RCP) [119, 131]. Simulation models need to improve their interconnectivities of monsoonal climate, extreme events of weather (floods and droughts), temporal and spatial variations in rainfall, increase in human population demands and scarcities in the future (Fig. 2).

Basic models used for hydrological studies are

- (a) Statistical hydrological models
- (b) Physical hydrological models.

At local scale (about 10,000 km²) to sub-basin level, physical-based hydrological models are used for climate change impact studies. For good performance of hydrological models, downscaled GCM data with more than one statistical method [17] must be used. Many hydrological predictions do not allow direct feeding of GCM output into a calibration-free hydrological model [30]. It is evident that atmospheric mechanisms influence soil

Fig. 2 Scheme of the climate variable transfer from global to catchment scale

moisture [10] which is one of the variables of hydrology at regional level [116].

6 Parameters used for future climate projections

6.1 Rainfall–runoff

Rainfall, soil moisture and land cover are important factors to predict runoff within a watershed. Future water fluxes can be calculated using rainfall–runoff models to analyze climate changes using satellite climate data as weather input [23]. In order to understand catchment hydrology, there is a need to estimate seasonal and annual values of rainfall, surface runoff, evaporation and recharge rates. Climate change may impact surface and groundwater resources [8] like severe floods, precipitation and temperature, surface runoff and base flow of catchment which affect ecosystem evapotranspiration, soil infiltration capacity and surface and subsurface flow regimes [92]. Future projected precipitation changes influence surface runoff and evapotranspiration, which

differ across the globe and are expected to have implications on freshwater ecosystems [22], yet there is a high-level agreement in terms of the magnitude and intensity of the change in flow in many regions [6]. Application of the same model in different regions for future runoff estimation gives different results [5] due to seasonal and inter-annual variations within the catchment [97] while average flows and the extreme events are affected by climate change [134]. The runoff is sensitive to temperature and rainfall as it shows different runoff amounts in arid and humid regions. This sensitivity also changes with the type of management practice. While considering precipitation changes with respect to climate change, there is a need to consider plant water use efficiency [61] because different factors show varying feedback effects to changing climate [109]. Macroscale and semi-distributed monthly water balance models are good at predicting the magnitude, timing of runoff and condition of water resources to simulate and predict the hydrological processes [43] like monthly runoff and soil moisture of basins in different climatic conditions.

6.2 Potential evaporation (PE)

Potential evaporation [5] is an important component in the water budget of the catchment and input to the rainfall–runoff model. Slow increase in PE, due to increasing temperature [23], has an impact on annual hydrological cycle [5]. Seasonal variability accounts for major impact on agriculture [58]. Impact of climate change on global water resources gives an overview about future water availability with increasing population [101]. Delayed beginning of rainy season and decrease in rainfall during rainy season may decrease annual discharge over long term due to an increase in potential evapotranspiration [97]. Rate of evaporation depends on total incoming net radiation, amount of rainfall, wind speed and direction and vapor pressure [71]. Changing climate scenarios of RCP are likely to predict impact of CO₂ on global climate, but it does not consider local climate feedback at global scale, such as plant physiology, number and spread area influence on local climate. India, which is a vast geographical region with varying climate, topography and geology, is also sensitive to greenhouse effect and requires very detailed knowledge on precipitation pattern and influencing parameters so as to incorporate in model structure to reduce bias and uncertainty. North-eastern states and south peninsular India are expected to experience increase in precipitation during summer and reduction in monsoon precipitation under global warming conditions [129].

6.3 Greenhouse gases and CO₂

Water scarcity severely affects food production and economic stability of any country. Global hydrological models (GHMs) forced with GCM and latest greenhouse gas concentration scenarios (RCP) provide future predicted changes of water bodies. According to RCP projections, an increment in temperature by 2 °C above the present state would affect nearly 15% of the global population through water scarcity [101]. Increasing temperatures across globe have considerable influence on cropping pattern [115] and changes in carbon balance of an ecosystem [100]. Global warming has a significant impact on water systems due to increasing troposphere temperature [120] and changes in extreme precipitation [7]. Climate changes are expected to increase climate-related risks to ecosystems due to increased heat, flooding, drought on natural and managed ecosystems like pest and disease prevalence, invasion of non-native species [48], ecosystem disturbances, land use change and landscape fragmentation [91]. Runoff is important in an ecosystem, as transpiration and interception processes are influenced by biological processes and affected by CO₂ concentrations and climate [38]. Vegetation interactions with CO₂ increase, and climate change magnitude and intensity coupled with seasonal timings have a significant influence on plant physiology [46]. Amount of carbon storage capacity varies with changing CO₂ and temperature [37].

6.4 Land cover and population growth

Climate change is associated with changes in temperature and precipitation intensity which further affect the hydrology of the region and exaggerated by land use change in the form of soil compaction and more impervious surface coverage. The impacts of climate change are more significant than LULC change in determining the basin hydrological response [65], but it is important to consider land use–land cover changes and associated flood and drought patterns when developing water resource management plans. Land use changes are intensified because of rapidly increasing population, agricultural production, deforestation, reclamation of wet lands, etc. These changes locally demand more water, while climate change results in low or high precipitation and increasing temperature and evaporation rates which leads to scarcity of water. Future water stress is calculated by the ratio of water use to availability [47] which can be attributed to economic growth, lifestyle changes and technological developments [101, 123]. The total amount of water and future water demand should be considered while modeling future hydrological responses to climate change [66]. The relative impacts of climate [103] and water withdrawals [24] need to be given priority for

better water management planning. The winter and summer seasonal changes cause water stress [138] in the catchment [24]. Future change in rainfall and population also leads to change in land use–land cover, further increasing soil degradation. Watershed base flow is affected by topography and geomorphology which influence the water storage properties and water transmission within a catchment [88]. Even in regions characterized by relatively low-intensity land use change, yet due to climate change, there have been clear reductions in base flow quantity and quality. Reduced base flows contribute to impairments known to affect fish, invertebrates and algal assemblages [96].

6.5 Flood

To investigate the flood frequency and re-occurrence, weather generator [69] can be used to generate time series of precipitation and temperature for long periods. Rainfall–runoff models predict future stream flow extremes and future flood risk assessment from climatic projections [124]. The model simulations show variations in both seasonal precipitation and stream flow which can be attributed to human-induced climate change and natural inter-variability of climate because future projections do not consider vulnerability of risk components which may change over time. Flood risk is expected to continue increasing due to increasing population, land use–land cover change, socioeconomic development and climate change in the coming decades [54, 121]. Increasing global sea levels (0.26–0.82 m) by 2100 results in more severe coastal floods [55]. GCM's output data are of relatively low spatial resolution, yet it enables large-scale analysis of floods in countries with data scarcity. Availability of continental and global-scale land use–land cover data supports large-scale forecasting of land use change dynamics that include the uncertainties associated with changing climate. Highly populated coastal areas are more prone to floods due to land use change, deforestation, extension of urban areas [32] and land subsidence causing hydrological changes [79]. Advances in mapping the flood hazard are possible with flood models integrated with suitable high-resolution topography [133]. Socioeconomic flood risk assessment based on an ensemble of the latest regional climate scenarios [3] and combining flood inundation maps with information on assets exposure and vulnerability [94] lead to an overall evaluation of the future flood risk and the related uncertainty.

7 General features of impact assessment procedure

Future changes in hydrological extremes like precipitation and temperature are still highly uncertain. According to [54], world climate changes are expected to result in severe rainfall extremes which are likely to differ from region to region. These uncertainties can be addressed using downscaling methods as the propagation of uncertainty through GCM, RCM and hydrological models [41] and identification of the most suitable emission scenarios [62]. In downscaling methods, it is usually assumed that the relationship between local-scale phenomena and regional climate is expected to be the same in the future; calibration of rainfall–runoff models depends on the climatic and temporal variability of model parameters [49]. The intensity of the hydrological response to the simulated climate change varies with the geological conditions of the area such as soils [116] and air temperature [11]. Model performance varies systematically with climatic conditions due to large differences in model structure, but the ensemble mean produces rather robust predictions [42]. Increasing or doubling of the atmospheric carbon dioxide concentration leads to negative impacts on groundwater resources as soil water deficit increases in root zone. Large amount of groundwater withdrawal and seasonal variations have small impact on groundwater. In impact studies, the site-specific models are important as they can be well calibrated with local physical conditions to simulate hydrological responses successfully [51]. Small changes in precipitation show large decrease in runoff due to increasing evapotranspiration. Local area hydrological response varies with geological conditions and climate change. Conversion of land use type results in decrease or increase in seasonal flows, flow intensities, evaporation and runoff. Such analysis must be considered while planning to build adaptation measures to overcome climate change for present and for future sustainable management efforts.

The climate change caused by local conditions on hydrology is less predictable and more diversified due to catchment properties like soil and topography which can add uncertainty to hydrological modeling [60]. Increase in greenhouse gases in atmosphere from the past 50 years results in continental runoff increase, heavy precipitation, flooding and drought [75]. RCMs are more efficient to capture the spatial variability of precipitation distribution at regional scale [70, 122] (Table 2).

8 Ensemble and multiple ensembles

The selection of climate models must be based on the range of changes in climate variables or the ability of climate models to simulate past climate. Ensemble of GCMs and RCMs with transfer of signal change into hydrological models shows different seasonal trends with the same output results [41]. Model behavior and the ability to simulate hydrological processes can vary in different climate regimes [90] as individual models differ regarding magnitudes and trend direction [105]. The result of hydroclimatic ensemble [81] approach is comparable, and future uncertainty can be evaluated. Averaging multi-model RCM ensembles based on different driving GCMs helps to reduce systematic errors. This confirms the importance of multi-model approach [42] to improve the consistency in future climate change projections [28]. Ensemble of hydrological model evaluates the range of climate variables [82] because of different processes of hydrological models. The relative contributions of hydrological models and GCMs to ensemble spread [45] differ spatially across the globe [101]. Ensembles of global-scale hydrological models give relative changes in hydrological indicators with different scenarios of global warming so as to understand the changes in hydrological indicators [117] at catchment level [40] like stream flow [19], spatial and seasonal variations [107]. If models are not calibrated with observed values, the results may be influenced by both model structure and calibration. In agricultural lands, the amount of water availability influences evaporation rate. Hence, soil moisture [113], rainfall [90] and evaporation variables must be included while assessing water demands for irrigation under climate change [78].

An inter-model comparison identified that not all models were consistent in explaining the present climate in terms of the mean, skewness and asymmetry [31]. Assessment of future climate with higher accuracy can be achieved by using ensemble mean [44], and the spread in projections of one single hydrological parameter for each ensemble is usually larger than the difference between the two ensemble medians [40]. The occurrence of time of extreme events during seasonal precipitation can be estimated using changes between precipitation projection model and climate model ensemble [35]. The analysis of individual RCM and its ensemble using the same driving force show different biases and give mixed results of seasonal temperature and precipitation. The population, climate change, expansion of agricultural land and global warming [95] are expected to change the regional climate. In order to assess the future climate change reliably, complete

Table 2 Literature collection using global, regional and hydrological models with SRES and RCP scenarios

References	Global climate model (GCM)	Regional climate models (RCM)	Hydrological model	IPCC projection	Climatic variable
Suh et al. [107]	HadGEM2-AO	4 RCMs of GRIMs, HadGEM3-RA, RegCM4, SNURCM, WRF	–	RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5	Surface air temperature
Li et al. [72]	2 GCMs of RMIP III	8 RCMs based on MM5, WRF, RAMS	–	A1B scenario	Future precipitation change (2041–2060)
Ruosteenoja et al. [98]	CMIP5	–	–	RCP 8.5	Monthly, seasonal and annual means of surface air temperature, precipitation and incident solar radiation
Soro et al. [104]	HadGEM2-ES	–	GR2 M	RCP 4.5, RCP 8.5	Monthly rainfall and temperature
Didovets et al. [29]	7 GCM	7 RCM	Soil and Water Integrated Model (SWIM)	RCP 4.5, RCP 8.5	Seasonal distribution of runoff
Keuler et al. [62]	MPI-ESM-LR, HadGEM2-ES, CNRM-CM5, EC-EARTH	COSMO-CLM	–	RCP 4.5, RCP 8.5	Climate change
[136]	–	SMHI-RCA, CNRM-ARPEGE	GBM	RCP 8.5	Climate change, surface temperature
Hosseinzadehtalaei et al. [50]	CMIP5	–	–	RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5	Impact of climate change on extreme precipitation
Chilkoti et al. [19]	–	CORDEX	HYMOD	Representative concentrated pathways (RCP) 4.5	Impact of the future climate on water availability
Karlsson et al. [58]	2 GCMs	HIRHAM5	MIKE SHE	RCP 4.5	Impacts on soil moisture dynamics and evapotranspiration
Lutz et al. [73]	CMIP5	–	–	RCP 4.5, RCP 8.5	Surface air temperature, precipitation
Oh et al. [84]	HadGEM2-AO	RegCM4, GRIMs, SNURCM, and WRF	–	RCP 2.6, 4.5, 6.0, 8.5	Seasonal monthly precipitation
Sunde et al. [108]	CMIP5	–	SWAT	RCP 2.6, 8.5	Stream flow, evapotranspiration
Brovkin et al. [12]	CMIP5	–	–	RCP 2.6, 8.5	Surface annual mean temperature
Jayasankar et al. [57]	CMIP5	–	–	RCP 2.6, 8.5	Seasonal cycle of rainfall

understanding of climate variability and land cover changes in past is required. The production of the ensemble method is affected by simulation skills and projection results of RCMs [72]. Ensemble simulation has been used in both weather forecasting and climate simulation to reduce the uncertainties and therefore improve the reliability of the simulation system. The predicted changes of precipitation are influenced by evapotranspiration and atmospheric moisture [122].

With the help of the ensemble modeling, it has been proven that soil surface temperature [136] and land

cover are responsible for precipitation changes. Multi-model and multi-projection approach to create probability distribution functions of future hydrological variables helps to better define the uncertainty linked to future climate. The probability distributions of future hydrological variables allow future impacts to be estimated. It is evident that uncertainty related to multi-model approach is greater than multi-projection approach [76]. Some ensembles incorporate additional processes like cloud formation, radiation balance, etc., in order to improve

Table 3 Supporting review papers on downscaling, RCM and hydrological modeling

Kidson and Thompson [64] Murphy [80]	A comparison of statistical and model-based downscaling techniques for estimating local climate variations An evaluation of statistical and dynamical techniques for downscaling local climate	Downscaling climate variables using statistical and local area mesoscale modeling (RAMS) for daily and monthly climate variables Dynamical and statistical methods are compared in terms of the correlation between the estimated and observed precipitation and temperature monthly Comparison of statistical and dynamical downscaling methods on the same grid A review of the different methodologies suggested in the literature to downscale GCM results at smaller spatial and temporal resolutions This review paper assesses the current downscaling literature, examining new developments in the downscaling field with reference to hydrological impacts
Casanueva et al. [14] Prudhomme et al. [89] Fowler et al. [34] Xu [132]	Towards a fair comparison of statistical and dynamical downscaling in the framework of the EURO-CORDEX initiative Downscaling of global climate models for flood frequency analysis: where are we now? Linking climate change modeling to impact studies: recent advances in downscaling techniques for hydrological modeling From GCMs to river flow: a review of downscaling methods and hydrologic modeling approaches	Climatic variable downscaling and the problems related to the practical application of appropriate models in impact studies. Advantages and deficiencies of the various approaches; challenges for the future study of the hydrological impacts of climate change are identified Different regional climate model simulations are used to analyze the effects of climate change impacts on hydrology
Graham et al. [41] Wood et al. [130]	Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods—a case study on the Lule River basin Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs	Downscaling climate model outputs for use in hydrological simulation to estimate each method's ability to produce precipitation and other variables of hydrology
Langousis et al. [68] Schmidli et al. [102] Wilby and Wigley [125]	Assessing the relative effectiveness of statistical downscaling and distribution mapping in reproducing rainfall statistics based on climate model results Statistical and dynamical downscaling of precipitation: An evaluation and comparison of scenarios for the European Alps Downscaling general circulation model output: a review of methods and limitations	Relative performance of direct statistical correction of climate model rainfall outputs using nonparametric distribution and statistical downscaling methods in reproducing the historical rainfall statistics at a regional level Inter-comparison of daily precipitation statistics as downscaled by six statistical and three dynamical methods Comparison of downscaling tools from GCM output
Wilby et al. [127] Kauffeldt et al. [59]	A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River basin, Colorado Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level	This study compared three sets of present and future rainfall–runoff scenarios using scenarios developed statistically downscaled GCM output, raw GCM output and raw GCM output corrected for elevation biases Uncertainty in future hydrological model prediction often due to weather inputs from climate models and model conceptualization. A multi-model system can collectively capture a representative spread of model uncertainty. This paper provides a technical review of 24 large-scale models to provide guidance for model selection
Praskievicz and Chang [87]	A review of hydrological modeling of basin-scale climate change and urban development impacts	Modeling is associated with uncertainty at the basin scale due to latitude, topography, geology and land use. Under scenarios of future climate change, water quality is determined by type of pollutants, surface runoff and urban development. Modeling studies should be based on scenarios constructed based on impacts of climate changes and future basin characteristics

Table 3 (continued)

Diaconescu et al. [27]	Evaluation of precipitation indices over North America from various configurations of regional climate models	This study presents the comparison of simulations from two Canadian regional climate models (RCMs) in simulating daily precipitation indices and the standardized precipitation index (SPI)
Giorgi [39]	Regional climate modeling: Status and perspectives	This paper presents a review of regional climate modeling in 1980s applications and possible future directions in RCM research
Jacob et al. [56]	An inter-comparison of regional climate models for Europe: model performance in present-day climate	The analysis of possible regional climate changes over Europe is simulated by 10 regional climate models to investigate possible systematic biases in the models to simulate the long-term mean climate and the inter-annual variability with respect to near-surface air temperature and precipitation during winter and summer
Mearns et al. [74]	Guidelines for use of climate scenarios developed from regional climate model experiments	The purpose of this guidance material is to develop, select and use procedures for evaluating, producing and using high-resolution climate scenarios
Teutschbein and Seibert [110]	Regional climate models for hydrological impact studies at the catchment scale: a review of recent modeling strategies	This article reviews applications of regional climate model (RCM) output for hydrological impact studies using single RCM and ensemble RCM

the climate simulations. These models can assess the potential impacts of future climate change at local scale.

9 Observations

A future projected change in precipitation varies depending on the type of GCMs, greenhouse gas emission scenarios, time horizon and season. Inter-model variability is always greater than inter-scenario variability. For future projections, hydrological model calibration can become a limitation factor. Climate models when combined with satellite observations indicate an increase in atmospheric water by 7% per degree Celsius of surface temperature.

To obtain more accurate and near real-time values, the hydrological response to the future climate including the indirect impact of climate changes like sea level increase, agricultural practices and type of land use, and increased water demand both domestic and agriculture must be considered. Increasing greenhouse gases increase evapotranspiration, thus affecting availability of water and crop yield. Some of the parameters affecting irrigation water requirements are type of crop, soil type, precipitation, temperature, cropping pattern, crop season, intensity of light, etc. However, the best results can be predicted by averaging all the available RCMs, as this technique can counterbalance the errors coming from different models. But different RCMs forced by the same GCM show significant errors which indicate that the processes and parameter selection are important while selecting the model response to the boundary forcing. RCMs are well functional at simulating some basin parameters or variables, but extreme events of rain cannot be significantly simulated.

For smaller regions, local climate mainly depends upon local feedback mechanisms because of which model selection should consider local climate, topography and vegetation conditions of the area. The sensitivity of runoff to climate change has direct influence on long-term soil moisture and basin soil types. As per research, the better method would be to use multi-downscaling techniques so as to consider the error propagation in hydrology. Local precipitation quantities depend on wet/dry day and regional-scale indicators like mean sea level pressure, specific humidity and geo-potential height. Based on the results from different models, it is possible to predict progressive modification over the coming decades in climate variables (Table 3).

10 Conclusions

To obtain reliable assessment requires the estimates of future climatic trends with perfection at regional and local scale. It is confirmed that modeling can address

the climate change and water resource problems. These problems are related to inefficiency of producing reliable parameters by GCMs due to their coarse resolution, downscaling and their limitations and tools used in hydrological modeling. The main uncertainty arises from the variations between GCMs and hydrological modeling in their spatial and temporal resolution. Ensemble and multiple ensembles give reliable mean precipitation and temperature with observed values. Simulations with different greenhouse gas scenarios are likely to produce increasing precipitation over India in near future [93]. The transfer of simulated values across different scales, models and regions is still a challenge. Models simulate catchment characteristics and variables at sub-basin scale. Few studies explain the reason for heavy precipitation as warm climate in central India [63], while few models fail to capture heavy precipitation with warming [77]. Hence, it is necessary to improve the model capacity, bias adjustment and uncertainty assessment while estimating future climate changes at local and regional scale.

The decision-makers make use of simulated future hydrological variables and trends to take long-term decisions based on sensitivity assessment, adaption and vulnerability to changing climatic conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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