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Streamflow Response to Climate Change in the Brahmani River Basin, India

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Abstract *Climate change can significantly affect the water resources availability by resulting changes in hydrological cycle. Hydrologic models are usually used to predict the impacts of landuse and climate changes and to evaluate the management strate- gies. In this study, impacts of climate change on streamflow of the Brahmani River basin were assessed using Precipitation Runoff Modeling System (PRMS) run under the platform of Modular Modeling System (MMS). The plausible hypothetical scenar- ios of rainfall and temperature changes were used to assess the sensitivity of stream- flow to changed climatic condition. The PRMS model was calibrated and validated forthe study area. Model performance was evaluated by using joint plots of daily and monthly observed and simulated runoff hydrographs and different statistical indicators. Daily observed and simulated hydrographs showed a reasonable agreement for cali- bration as well as validation periods. The modeling efficiency (E) varied in the range of 0.69 to 0.93 and 0.85 to 0.95 for the calibration and validation periods, respec- tively. Simulation studies with temperature rise of 2 and 4°C indicated 6 and 11% decrease in annual streamflow, respectively. However, there is about 62% increase in annual streamflow under the combined effect of 4°C temperature rise and 30% rainfall increase (T4P30). The results of the scenario analysis showed that the basin is more sensitivetochangesinrainfallascomparedtochangesintemperature.*

I. INTRODUCTION

Global climate change caused by increasing atmospheric concentration of carbon dioxide and other trace gasses, as well as anthropogenic activities are expected to alter regional hydrologicalconditionandresultinavarietyofimpactsonwaterresources.Suchhydrologic changeswillaffectnearlyeveryaspectofhumanwellbeing,fromagriculturalwater productivity and energy production to flood control, municipal and industrialwatersupply,andfishandwildlifemanagement(RagabandPrudhomme2002;XuandSingh2004;Minvilleetal.2008).Severalstudies(WhitfieldandCannon2000;Muzik2001;RisbeyandEntekhabi1996) have shown that small perturbations in the magnitude and/orfrequencyofprecipitationcanresultinsignificantimpactsonthemeanannualdischarge.Quantifyingstreamflowresponsetopotentialimpactsofclimatechangeandvariabilityisthefirststeptodevelopinglong-termwaterresourcemanagementplans.Anunderstandingofthehydro-logicalresponseofariverbasinunderchangedclimaticconditionswouldhelptoresolvepotentialwaterresourcesproblemsassociatedwithfloods,droughtsandavailabilityofwaterfor agriculture, industry, hydropower, domestic and industrial use, andto developtheadaptationandpreparednessstrategiestomeetthesechallenges,incaseoftheiroccurrences.India is a large developing country with nearly two-thirds ofthepopulationdependingdirectlyonagriculture,whichis highlyclimate sensitive. Any temporalandspatialvariationsinrainfallhavereflectiveeffectonwateravailabilityinbothirrigatedandrainfedareas,affectingtheagriculturebasedeconomyof the region.Therearepreliminaryreportsthattherecenttrendofdecline inyields of rice andwheat in Indo-Gangetic plains could have been partly dueto weatherchanges(Aggarwal et al. 2004). Hydrologic modeling of different river basins ofIndiausingSWAT (Soil and Water Assessment Tool; Arnold et al. 1999) in combinationwiththeoutputsoftheHadleyCentreRegionalClimateModel(HadRM2)forthecontrol(1981–2000)andfuturegreenhouse gas(GHG) (2041–2060) climate data indicatedanincreaseintheseverityofdroughtandintensityoffloodsindifferentpartsofthecountry (Gosain et al.

2006). The study also revealed that the increase in rainfallduetoclimatechangedoesnotresultinanincreaseinthesurfacerunoffasmay begenerallypredicted.Mirza(1997)reportedchangesinmeanannualrunoffintherangeof 27 to 116% in the nine sub-basins of the River Ganga at doubledCO_2conditionandthattherunoffwasmoresensitivetoclimatechangeinthedriersubbasinsthaninthewettersubbasins.Sharmaetal.(2000)reported adecreaseinrunoffby 2to8%intheKosibasindependinguponthe areasconsideredandmodelsusedunderthescenariooftemperatureriseby4° Candnochangesinprecipitation.Mehrotra(1999)observedthatbasinsbelongingtorelativelydryclimaticregionaremoresensitivetoclimatechangescenarios.TheSher(drysub-humid)andtheKolar(moistsub-humid)are comparatively more sensitive to climate change, whereas Damanganga(humid)isleast sensitive. The greater sensitivity of the Sher and the Kolar basin wasattributedto the aridity of the basin, higher evapotranspiration rate, andregional metamorphiccharacteristicsofthebasinthatgovernsthemoistureretentioninthebasin.Aroraetal.(2008)reported10,28 and43%increaseinsnowmeltrunoffand7,19and28%increase in total streamflow runoff in Chenab River basin for T+1°C, T+2°C andT +3°C scenarios, respectively. Singh et al. (2006) reported increase in summer stream- flow in glacierized Himalayan basin with a temperature rise of 2°C, whereas ±3.5% change in streamflow with ±10% change in rainfall. Further, Singh and Bengtsson (2005) found that annual snow-melt was reduced by about 18% for a T+2°C scenario for the snow-fed basin, whereas it increased by about 33% for the glacier-fed basin in the Himalayan region. Under warmer climate, reduction in snowmelt from the snowfed was due to availability of lesser amount of snow in the basin. They also found that the snowfed basins are more sensitive in terms of reduction in water availability due to compound effect of increase in evaporation (attributed to warmer climate and increase in snow free area with time due to disappearance of snow) and decrease in melt. As future climate changes will impact regional water availability, region specific assessments of climate change impact are of utmost importance for regional water resources planning andmanagement. The most commonly used approach for studying the effects of climate change on hydrology and water resources involves employing hydrological models at the basin or watershed scale driven by climatic data obtained either directly from the General Circulation Model (GCM) outputs or from hypothetical or GCM-based scenarios of climate change. Hydrologic models provide a framework to conceptualize and inves- tigate the complex effect of both climate and landuse changes (Leavesley1994; Xu2000), and have been applied in many studies in order to assess the effect of land use and climate changes on runoff. Physically based distributed models that represent the spatial variability of landuseand climatic characteristics are the most useful for studying hydrologic effects of landuse changes and climatic variability for large basins (Borah and Bera2003). The scientific literature of the past two decades contains a large number of research papers dealing with the application of different hydrologic models to the assessment of the potential effects of climate change on a variety of water resource issues. For example, Hattermann et al. (2011) applied semi-distributed model SWIM (Soil and Water Integrated Model; Krysanova et al. 1998) for assessing climate change impact on water resources in the German State of Saxony-Anhalt; Bekele and Knapp (2010) applied SWAT model in the Fox River watershed to assess the impact of potential climate change on water supply availability; Veijalainen et al. (2010) used Watershed Simulation and Forecasting System (WSFS; Vehviläinen et al. 2005) to simulate the hydrological effects of climate change on water resources and lake regulation in the Vuoksi watershed in Finland; Minville et al. (2009) applied physically-based distributed model Hydrotel (Fortin et al. 2001) in the Peribonka River water resource system (Quebec, Canada) to evaluate the impacts on hydropow- er, power plant efficiency, unproductive spills and reservoir reliability due to changes in the hydrological regimes under projected climate change scenarios; and Qi et al. (2009) used Precipitation Runoff Modeling System (PRMS; Leavesley et al. 1983) for assessing potential impacts of climate and land use changes on the monthly stream- flow of the Trent River basin on the lower coastal plain of eastern North Carolina. Passcheir (1996) compared five “event” (single runoff event) models and 10 contin- uous hydrological models for rainfall-runoff modeling of the Rhine and Meuse basin for land use impact modeling, climate change impact modeling, real-time flood forecasting and physically based flood frequency analysis. Four continuous models, namely, PRMS, SACRAMENTO (Burnash1995), HBV (HydrologiskaByransVatten- balansavdelning; Bergstrom and Forsman1973) and SWMM (Storm Water Manage- mentModel; Huber 1995) and one event model HEC-1 (U.S. Army Corps of Engineers Hydrologic Engineering Centre hydrological model; Feldman 1995) were evaluated as the best ones. The HEC-1 and HBV model models were evaluated as the most appropriate for flood frequency analysis, the HBV and SLURP (Semi-distributed Land Use Runoff Process; Kite 1995) models for climate change impacts on peak discharges, and the PRMS and SACRAMENTO model for assessment of climate change impact on discharge regimes. In this paper an attempt has been made to: (1) test the U.S. Geological Survey’s Precipitation Runoff Modeling System (PRMS) for modeling streamflow of the Brahmani Riverbasin,and(2)toperformahydrologicsensitivityassessmentandquantifythemagnitudes of hydrologic response to possible climate changes in the basin. The paper first presentsthe maincharacteristicsofthebasin,followedbyhydrologicalmodels,dataused,delineationof basin into hydrological response units (HRUs), and sensitivity of streamflow to different hypothetical climate changescenarios.

II. STUDY AREA AND DATA DESCRIPTION

Study Area

The Brahmani River basin is located in the eastern part of India, and lies between latitudes 20°30′10″ and 23°36′42″N and longitudes 83°52′55″ and 87°00′38″E. The basin is situated between Mahanadi basin (on the right) and Baitarani basin (on the left). Chhotanagpur Plateauintheeastandsouthboundthebasin,inthenortharidgeseparatesitfromMahanadi basin, and the Bay of Bengal and the Baitarani basin in the east of the basin. It has a total catchment area of 39,313.50 km^2 and is spread over Orissa (57.3% of the basin area), Jharkhand (39.2% of the basin area) and Chhattisgarh (3.5% of the basin area) states of Indian Union. The basin is composed of four distinct sub-basins, namely Tilga, Jaraikela, GomlaiandJenapur(Fig.1).TheBrahmaniRiverrisesnearNagrivillageinRanchidistrict of Jharkhand at an elevation of about 600 m and travels a total length of 799 km before it outfallsintotheBayofBengal.Thebasinhasasub-humidtropicalclimatewithanaverage annualrainfallof1305mm,mostofwhichisconcentratedinthesouthwestmonsoonseason ofJunetoOctober.TheBrahmaniRiverbasinisawatersurplusbasinandkeysourceofwater supplies for different towns and industries, and for irrigation in the state of Orissa, India. However, rapid economic development and population growth in this region have caused concernsovertheadequacyofthequantityandqualityofwaterwithdrawnfromtheBrahmani River in the future. Rainfed agriculture is predominant except in lower deltaic parts where irrigationplaysamajorrole.Thefloodisacommonfeatureinthedeltaregion.Considering thelandandwaterresourcesproblems,andavailabilityofhydrometeorological,soil,landuse and other data Brahmani basin was selected as the study area for the presentstudy.

Data

Daily streamflow and rainfall data (1979–2003) of four stream gauging stations, namely, Tilga, Jaraikela, Gomlai and Jenapur were collected from Central Water Commission

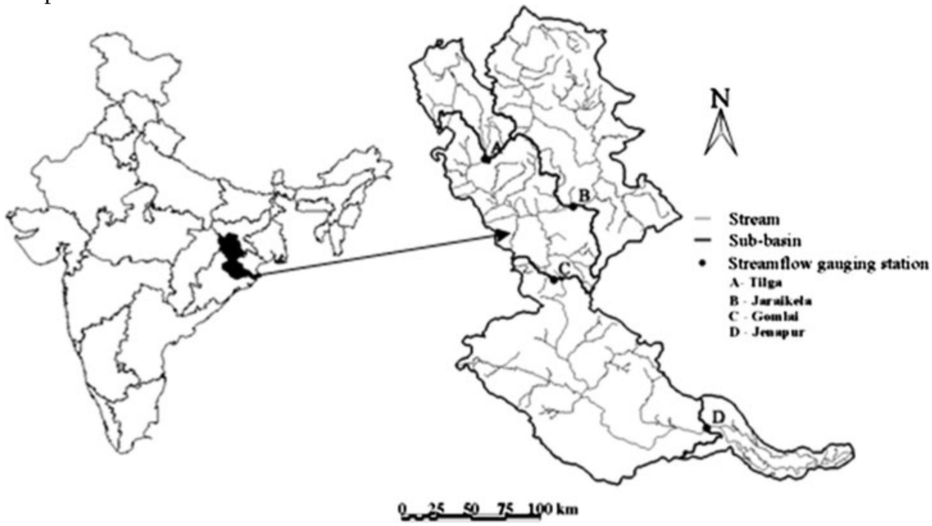

Fig. 1 Location map of the Brahmani River basin

(CWC). Daily rainfall and temperature data for 11 stations spread over the basin were collectedfromIndiaMeteorologicalDepartment(IMD),Pune.Catchmentmapwithlocation of streamflow gauging stations is collected from Central Water Commission, and soil and land use maps were collected from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP). Toposheets of 1:250,000 scale with Universal Transverse Mercator (UTM) projection and 200 ft (60 m) contour intervals were downloaded from USGS website.Thesemapswereprocessedundergeographicinformationsystem(GIS)andimage processing environment with the help of PCI Geomatica (PCI Geomatics) and TNTmips (MicroImages, Inc.) software for delineation of basin into sub-basin andHRUs.

III. METHODOLOGY

Hydrologic Model

The U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS), which is embedded in the Modular Modeling System (MMS), was selected for this study. MMS is an integrated system of computer software designed to provide a framework for the development and application of models to simulate a variety of water, energy, and biogeochemical processes (Leavesley et al. 1996, 2002). MMS uses amodule library containing algorithms for simulating variety of hydrologic and ecosystem processes. The central model in MMS is the Precipitation-Runoff Modeling System (Leavesley et al. 1983, 2002). PRMS is a modular design, distributed parameter, physically based watershed model designed to analyze the effects of precipitation, climate, and landuse on streamflow and other general basin hydrology (Leavesley et al. 1983). The model simulates basin response to normal and extreme rainfall and snowmelt, and can be used to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil water relationships, and groundwater recharge. Parameter optimization and sensitivity analysis capabilities are also provided to fit selected model parameters and to evaluate their individual and joint effects on model outputs (Leavesley et al. 1983,2002).

Distributed parameter capabilities of the model are provided by partitioning the basin into smaller modeling subunits where the runoff response is considered to be homogeneous. These units are called hydrologic response units (HRUs) and are typically based on physiographic characteristics such as soil type and infiltration rate, slope, aspect, land cover/land use, and altitude. In PRMS, the basin is conceptualized as a series of reservoirs (Fig. 2). These reservoirs include interception storage in the vegetation canopy, storage in the soil zone, subsurface storage between surface of watershed and the water table, and groundwater storage. Simulated streamflow from PRMS is a summation of three flow components: 1) surface flow; 2) subsurface flow; and 3) groundwater flow. Surface or overland flow is generated from saturated soils and runoff from impervious surfaces. Subsurface flow is shallow subsurface flow that originates from soil water in excess of available water-holding capacity of the soil. Groundwater flow, or baseflow, is sourced from both the soil zone and subsurface reservoir. The sum of the water balances of all HRUs, weightedby unit area, produces the daily watershed response. PRMS uses daily values of precipitation, and minimum and maximum temperature as input. The model can be operated in daily and storm mode. In this study, the daily mode was used for modeling daily and monthlystreamflow.

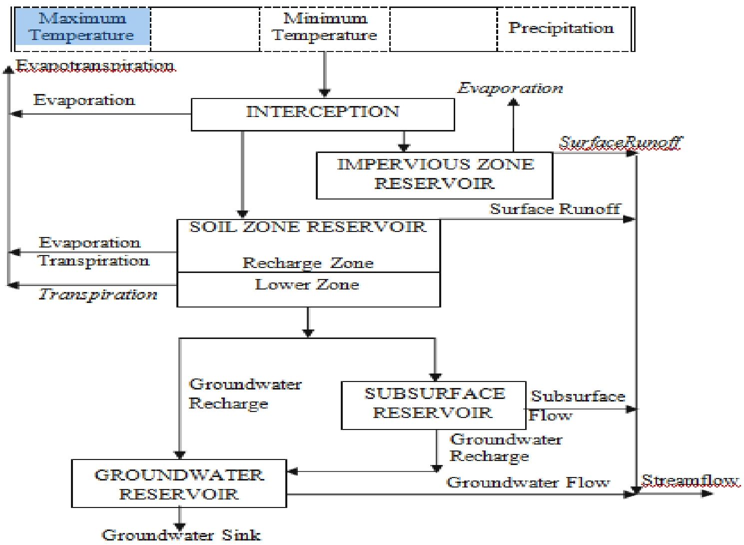

Fig. 2 Conceptual diagram of Precipitation-Runoff Modeling System (Leavesley et al. 1983)

In PRMS model, interception is computed as a function of vegetation cover density and the storage available on the predominant vegetation type of an HRU. Daily surface runoff from rainfall is computed using a contributing area concept. The percent of an HRU contributing to surface runoff is computed as a nonlinear function ofantecedentsoilmoistureandrainfallamountusingthefollowingequation:

$$ca\_percent = smidx\_coef \times 10^{(smidx\_exp \times smidx)} \quad (1)$$

$$smidx = soil\_moist \times 0.5 \times net\_rain \quad (2)$$

$$srp = ca\_percent \times net\_rain \quad (3)$$

wheresmidx_coef and smidx_exp are coefficients and exponents in the nonlinear contrib- uting area algorithm, respectively, soil_moist is the soil moisture content for each HRU, net_rain is rain minus interception for the HRU, and srp is the surface runoff from the pervious area. In case of impervious areas, rainfall or snowfall first satisfies the retention storage and then remainder becomes available for surface runoff.

The soil-zone reservoir is treated as a two-layered system (Fig. 2). Losses from the rechargezoneoccurasevaporationandtranspiration;lossesfromthelowerzoneoccuronly through transpiration. Three different procedures are available for estimation of potential evapotranspiration, namely, from pan-evaporation data, Hamon method and Jensen-Haise method. When the soil zone reservoir reaches maximum storage capacity, additional infil- trationisroutedtothesubsurfaceandgroundwaterreservoirs.Theapportioningofsoilwater in excess of the maximum storage capacity to the subsurface and groundwater reservoirs is done using a user-defined daily groundwater recharge rate. The subsurface flow is consid- eredtoberelativelyrapidmovementofwaterfromunsaturatedzonetostreamchannel.The subsurfaceflowiscomputedusingreservoirroutingsystem,andreservoircanbedefinedas linearornonlinear.Thegroundwaterreservoirsimulatestheslowercomponentofflowfrom the groundwater zone. It is conceptualized as a linear reservoir and is assumed to be the source of all baseflow. The vertical movement of water from a subsurface reservoir to a groundwater reservoir is computed as a function of the current volume of storage in subsurface reservoir and a linear routing coefficient. The movement of water through the groundwater reservoir to points outside the surface drainage boundary is treated using a groundwater sink, which is computed as a function of storage in the groundwater reservoir andgroundwaterroutingcoefficient.Theequationsusedforcomputationofdifferentwater balance components are described in Leavesley et al.(1983).

HRU Generation

Contoursat60mintervalsweredigitizedaftergeo-referencingthetoposheetsforgenerationof the Digital Elevation Models (DEM). DEM layer was developed with 30 mofspatialresolution, using triangulated irregular network interpolation with linearinterpolationalgo- rithm.Theelevationlayerwasslicedintothethreeclassesrepresentinghilly,plateau,andplainregion.Seedpoints/pourpointswereplacedontheDEMlayeraccordingtogeograph-icallocationofthestreamflowgaugingstationstodelineatesub-basin,andthebasinwasdividedintofoursub- basinsnamelyTilga,Jaraikela,Gomlai,andJenapur.Finally,thematicmapofsoilwithsixtexturalclassesandlandusemapwithfourclassesweregenerated.Slicedelevationlayer,soillayerandlanduselayerwereoverlaidfordelineationofbasinintoHRUs.DifferentHRUparameterssuchasarea,elevation,slope,landuseandsoiltypeofeachHRUwerethenextractedthroughtheHRUsvectorlayerandindividualthematiclayer.For distributed hydrological modeling the Brahmani River basin was delineatedinto66spatially distributed HRUs. Physiographic undulation is quite prominent in theentirebasinandelevationvariedbetween28to1159m.Hilly,plateauandplainregion comprisesof3.1, 41.5 and 55.40% of the total catchment area, respectively. The slope varied between 0.28 and 20.52% with a mean slope of 6.13%. Cultivated land (69.86%) is the major land use class followed by forest (27.73%) and settlement (0.23%). The water bodies occupy 2.18% ofthecatchmentarea.Sandyloamisthemajorsoiltypeoccupying43.6%ofthecatchment area followed by loamy sand (22%), clay loam (15.6%), silt loam (13.9%) , loamy (4.8%), clay (0.1%) soil. The area, elevation, slope, land use and soil type extracted for each HRU were used as input to the hydrologicalmodel.

Calibration and Validation ofModel

Determination of input parameter values is a critical step for application of hydrological model.DailyrainfallandtemperaturedatawereusedasinputtothePRMSmodelandmodel wascalibratedandvalidatedfortheperiod1980–84and1984–86,respectively,bymatching the simulated and observed streamflow of Jenapur gauging station. The availability of concurrent streamflow and climate data primarily dictated the selection of the time periods used for model calibration and validation.

The model was first run in a daily runoff- prediction mode with parameter values estimated for the basin. After selection of initial parametervalues,sensitivityanalysiswasusedtoidentifythesensitiveparametersthataffect the prediction of daily streamflow during the calibration period. Results of the sensitivity analysis indicated that the basin response is more sensitive to the monthly temperature adjustment factor for calculation of PET (jh_coef), soil moisture related parameter SOIL_- MOIST_MAX and subsurface flow related parameter SSRCOEF_ LIN and surface runoff related parameter CAREA_MAX, SMIDX_EXP and SMIDX_COEF. These parameters were selected for the calibration process and realistic model parameter and coefficient values for the study area were estimated so that the PRMS model closely simulates the hydrological processes of the basin. A trial and error adjustment of the selected parameters was performed until a reasonable match between observed and simulated streamflow hydrographs was obtained. Simulation results were examined both graph- ically and statistically to assess the model performance. Statistically model perfor- mance at daily and monthly temporal scales was evaluated using the standard Nash- Sutcliffe coefficient (*E*) (Nash and Sutcliffe 1970), index of agreement (d_1) (Legates and McCabe 1999) for the calibration and validation periods. In addition, the com- monly used statistical indicators such as root mean squared error (RMSE) and coefficient of determination (r^2) were also used. Following equations were used for calculating the values of RMSE, r^2, E, andd_1.

Climate ChangeScenarios

Thegeneralcirculationmodels(GCMs)aretheprimarysourceofdataforuseintheclimate change impact assessment studies. Although there have been great advances with GCMs predictions over the past decade, large uncertainties are there regarding future changes in climateforparticularregionsorbasins.Infact,differentGCMsprovidedifferentestimatesof changesinprecipitationandtemperature.Hydrologicalperturbationstudiesusingthesimple anddirectapproachofhypotheticalscenariosofchangesintemperatureandprecipitationare usefultoexplorethepotentialboundsofhydrologicalresponseforanybasin(NashandGleick1991).Theyareusuallyadop tedforexploringsystemsensitivitypriortotheapplicationofmore credible,model-basedscenarios(Mearnsetal.2001).Xu(2000)considered15hypothetical climate change scenarios with different combination of temperature (1, 2, 3, and 4°C) and precipitation(0,±10and±20)changesformodelingclimatechangeimpactonwaterresources inCentralSweden.BekeleandKnapp(2010)generatedeightdifferentclimatechangescenar-iosdatafortheFoxRiverwatershedusingdeltachangeapproach.Theyconsideredprecipita-tionchangesof+127,0(nochange)and−127mm,andtemperaturechangesof0,1.7and3.3°C basedonthereviewofGCMoutputs.Inthepresentstudy, weconsideredarangeofclimate changecaseswithrainfallchangesvaryingfrom±10to30%withanincrementof10%and temperature changes varying from 0 to 4°C with an increment of 2°C. The changes in temperatureandrainfallconsideredherearebasedontheoutputsofdifferentGCMs(Table1) forthestudybasin.MostoftheGCMspredictedabout4°Cincreaseinmeantemperatureduring 2080(2070–2099)exceptNIES(NationalInstituteforEnvironmentalStudies)GCM,which predicated4.9°CincreaseinmeantemperatureunderA2emissionscenarios.Hence,maximum increaseof4°Cinthemeantemperatureisconsideredinthisstudy.Therearelotsofvariations in the mean monthly rainfall predicted by different GCMs and average annual changes in rainfallvariedintherangeof−3.30to29.6%.Withdifferentcombinationoftemperatureand rainfallchanges,14differenthypotheticalscenarioswereconsidered.Observedtimeseriesof rainfallandtemperaturedata(1980–1990)weremodifiedbyaddingchangesintemperatureto historic temperature series, and by multiplying by changes in rainfall to rainfall series (Xu2000).Thesescenariosdonotnecessarilypresentarealisticsetofchangesthatarephysically plausible. Hydrological response was then simulated for the period 1980–1990 under the presentclimaticconditions(i.e.,nochangeinrainfallandtemperature)aswellas14hypothet- ical climate change scenarios representing futureclimate.

IV. RESULTS ANDDISCUSSION

Calibration and Validation of HydrologicalModel

ThePRMSmodelwascalibratedfortheperiod1980–84andvalidatedfortheperiod1984–86 by matching the simulated and observed streamflow data. Daily observed and simulated streamflowhydrographs showed a reasonable agreement for both calibration and validation period(Fig.3).Itisclearfromthefigurethatthoughthemodelcouldproducethesimilartrend betweenobservedandsimulatedstreamflowhydrographs,butitcouldnotcapturesomeofthe peak flow events. In general, model underestimated the daily streamflow for large peaks occurringprimarilyduringJuly–August.Thisunderestimationofstreamflowmaybeattributed toimprecise/unevenrepresentationofspatialdistribution ofrainfallandunderestimationof arealrainfallinsuchalargebasinaslocalamountofrainfallmayvarygreatlyacrossthebasin. Thedifferentstatisticalindicatorscomputedusingmeanmonthlystreamflowforthecalibration

Table 1 Projected changes in the mean temperature and rainfall in the basin

Model	A2			B2		
	2020	2050	2080	2020	2050	2080
Changes in mean temperature (°C)						
CCCMA-CGCM2[a]	1.50	2.50	3.30	0.90	1.00	1.60
CSIRO-MK2	0.80	1.80	3.20	1.00	1.80	2.50
ECHAM4	0.50	1.70	3.30	0.80	1.40	2.30
GFDL–R30	0.70	1.90	3.40	0.80	1.60	1.90
HadCM3	0.80	2.30	3.90	0.90	1.70	2.80
NIES	1.00	2.40	4.90	1.10	2.30	3.70
Changes in precipitation (%)						
CCCMA-CGCM2	−1.30	−0.75	12.40	−2.25	8.20	3.50
CSIRO-MK2	−3.30	4.00	16.70	5.40	3.60	9.80
ECHAM4	5.80	18.10	29.60	11.30	16.90	23.00
GFDL–R30	2.60	10.40	9.80	5.20	6.70	10.70
HadCM3	6.20	6.50	13.10	5.40	9.30	10.30
NIES	2.00	9.00	16.45	5.10	6.25	12.60

4.2 Hydrological Response of Streamflow to Climate Change
Resultsofthesimulatedscenariosrevealedthatthestreamflowissensitivetobothtemperature andrainfallchanges,butchangesinrainfallhaveagreatereffectonstreamflow.A4°Crisein temperature resulted in 11.40% decrease in annual streamflow, whereas 10% decrease in rainfall resulted in 22.90% decrease in annual streamflow (Fig. 4). As shown in Fig. 4, a 10% decrease in rainfall resulted in 25.00, 12.40, and 21.10% decrease in streamflowduring monsoon, pre-monsoon, and post-monsoon season respectively, whereas 4°C increase in temperatureresultedin12.00,2.70,and11.20%decreaseinstreamflowduringthe same.

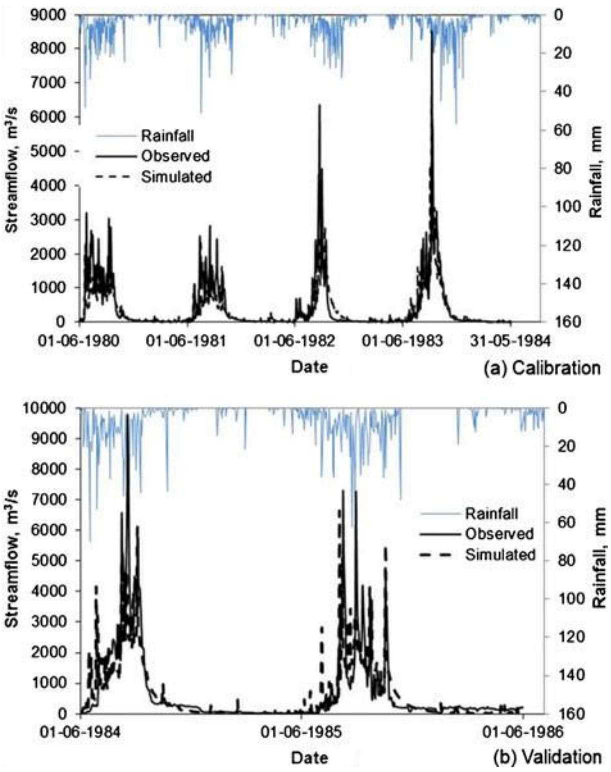

Fig. 3 Observed and simulated hydrographs at Jenapur outlet for calibration and validation periods

seasons. The combined effect of rainfall and temperature changes is shown in Fig. 5. The magnitude of changes in mean annual streamflow varied in the range of −32.90 to 62.20%

(Fig.5).Atemperatureriseof4°Canda10%decreaseinrainfall(T4P-10)resultedin32.90, 35.00,14.70,31.70,and20.80%decreaseinannual,monsoon,pre-monsoon,post-monsoon and winter season streamflow, respectively. However, 4°C rise of temperature coupled with 30%increaseinrainfall(T4P30)resultedin62.20,72.50,38.50,51.90and29.60%increasein annual, monsoon, pre-monsoon, post-monsoon and winter season streamflow, respectively. Analysis of monthly streamflow data revealed that there are significant changes in mean monthlystreamflow,particularlyduringmonsoonmonths(Table3).Maximumabsolute

Table 2 Model performance statistics for the calibration and validation periods

	Calibration				Validation	
	80–81	81–82	82–83	83–84	84–85	85–86
RMSE	77.20	75.70	98.20	68.40	132.90	55.00
R^2	0.96	0.98	0.78	0.99	0.94	0.96
E	0.81	0.69	0.74	0.93	0.85	0.95
d_1	0.83	0.78	0.80	0.90	0.85	0.88

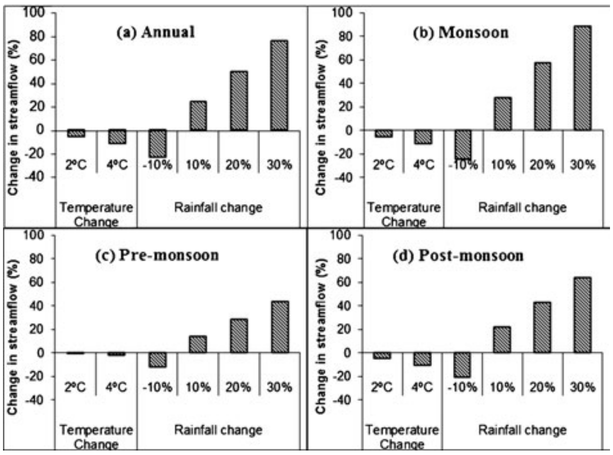

Fig. 4 Response of streamflow to potential rainfall and temperature changes

changesinstreamflowoccurredduringthemonthofJulywhenstreamflowwasalmostdoubled with30%increaseinrainfall,andminimumabsolutechanges(32.90%)occurredinthemonth ofJanuaryundersame(i.e.,30%increase)scenariosofrainfallchange.With30%increasein rainfalland4°Cincreaseintemperature,themagnitudeofchangesinmeanmonthlystreamflow ranged from 83.40% (July) to 26.90% (January). A maximum decrease of 37% (July) was estimatedwith4°Cincreaseintemperaturetogetherwith10%decreaseinrainfall.Theeffects of 10% decrease in rainfall changes in annual and seasonal streamflow is about two times greaterthanthatof4°Cincreaseintemperature.Thisindicatesthatchangesintemperaturehada relatively lesser effect on the magnitude of annual and seasonal streamflow as compared to rainfallchangesintheBrahmanibasin.Thiscouldbeattributedtosub-humidclimaticcondition inthebasinwithlowerpartofthebasinbeinglocatedinthecoastalregion. Modelsimulationresultsaresubjecttovarioussourcesofuncertainty.Someuncertainties areinherentinthemodelstructureandsomeareduetoerrorsinthecalibrationandparameter estimation. The accuracy of the model calibration is dependent on the accuracy of the input data.Precipitationdataisoneofthemostcriticalinputvariablesinanyhydrologicalmodeling studies and errors associated with the distribution of rainfall over the basin affect the model results.Lackofreliablemeteorologicalandhydrologicaldataofsufficientlengthareoneofthe

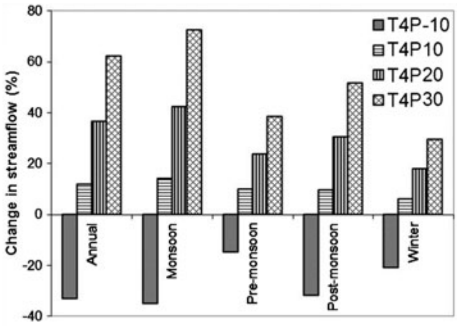

Fig. 5 Response of streamflow to combined effect of rainfall and temperatur

challengesin model calibration. Land use and land cover changes are also crucial factors affectingthehydrologicsystemofthecatchment.Thestudyassumesthatmodelcalibrationwill holdinfuturescenariostoo.Thelandusechangeshavebeenassumedtobestaticandonlythe effect of changes temperature and rainfall has been studied. The hypothetical scenarios considered in this study compute the changes in climate by uniformly changing the current valuesofdaily temperatureand rainfallforallthemonthsoftheyearanddonotaccountfor changesinvariance.ConsiderationofmorescenariosusingoutputsofdifferentGCMswillhelp toreducetheseuncertainties.TheuseofnumberofGCMsoutputalongwithlandusechanges will help more reliable estimation of changes in streamflow due to climatic and land use changes in thebasin.

V. CONCLUSIONS

Assessmentofclimatechangeimpactonwaterresourcesisveryimportantforitsplanningand management,anddevelopingsuitableadaptationstrategies.Inthisstudyprecipitationrunoff modelingsystem(PRMS)wasusedtoassesstheimpactsofclimatechangesonthestreamflow oftheBrahmaniRiverbasin.Themodelwasfoundtoperformreasonablywellinsimulating dailyandmonthlystreamflowhydrographsforbothcalibrationandvalidationperiods.Differ-entstatisticalperformanceindicatorsshowedthatthePRMSmodelwasabletosimulatethe monthlystreamflowreasonablywell.Themodelingefficiency(E)variedintherangeof0.74to 0.93 and 0.85 to 0.95 during calibration and validation period, respectively. Hypothetical climate change scenarios, considered based on the review of different GCMs outputs, were usedtosimulatetheresponseofstreamflowtoclimatechangeandcomparedwiththepresent climate condition (base line). Hypothetical scenarios considered include individual as well combinedscenariosofrainfallandtemperatureschanges.Simulationresultsindicatedabout6 and11%decreaseinannualstreamflowwithtemperatureriseof2and4°C,respectively.A10% increaseinrainfallresultedin24%increaseinannualstreamflow.Underthecombinedeffectof rainfallandtemperaturechanges,annualstreamflowincreasedbyabout62%with4°Criseof temperatureand30%increaseinrainfall(T4P30).Resultsofthescenarioanalysisindicatedthat thestreamflowintheBrahmaniRiverbasinismoresensitivetochangesinrainfallascompared tochangesintemperature. Theresultspresented inthispaperarenotthepredictions,butare plausiblechangesinthestreamflow.Thehypotheticalscenariosconsideredinthebasindonot account for the changes in the variance, and do not necessarily represent the future climate. Futurestudyshouldfocusoneffectoflandusechangeandconsiderationofnumberof GCMs output to arrive at more reliable estimation of the streamflowin thebasin.

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