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CLIMATE CHANGE IMPACT ASSESSMENT ON THE HYDROLOGY OF A SEMI-ARID RIVER BASIN

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In present study, physical based Water and Energy Budget - based Distributed Hydrological Model (WEB-DHM) was applied to investigate the intra-basin river runoff and to elucidate the potential impacts of climate change on hydrology in the Soan River Basin, Pakistan, a semi-arid and poorly gauged basin (PGB). The model performance was evaluated in terms of river discharge and soil moisture. WEB-DHM simulated surface soil moisture was validated by soil moisture assimilated by Land Data Assimilation System developed by the University of Tokyo (LDAS-UT). WEB-DHM was derived with bias corrected precipitation and other parameters from four Atmosphere-Ocean General Circulation Models (AOGCMs). The analysis of twenty years simulated daily discharge for the past (1981-2000) and future (2046-2065) showed that it is likely that flooding trend will increase in the future. However, it is about as likely as not that the drought will intensify in the future. The study demonstrate an example for climate change impact assessment on hydrological processes in a PGB.

Key Words: *WEB-DHM, PGB, flood, drought, Semi-arid basin*

1. INTRODUCTION

Water is an essential component for sustaining quality of life on earth and for sustainable socio-economic growth. In today's environment of growing scarcity, the incompatible claims for more and more water are imposing pressure for improved hydrological modeling and decision making. The general impacts of climate change on water resources have been brought out by the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[1,2]. Barriers to widespread use of climate change projections in water resources studies include data availability and the knowledge to appropriately use this information for specific watershed studies[3]. Climate change studies require observations to be calibrated/validated and consistent, and to provide adequate temporal and spatial sampling over a long period of time[4]. However; in developing countries the river basins termed as poorly gauged basins (PGBs), the spatio-temporal data is either missing or less detailed to represent the clear picture. Prediction in PGBs is a tremendous challenge that is needed to be addressed in the modern hydrology. The present paper concentrate on the following objectives: i) To propose an integrated physical based Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM, detailed description in Wang et al., 2009[5]) to simulate hydrological processes in the Soan River Basin, Pakistan, a poorly gauged basin; ii) To drive WEB-DHM by incorporating global data-sets to solve poor coverage of hydrological data issue in the basin; iii) To evaluate the model performance to simulate river runoff and soil moisture; iv) To introduce additional module in WEB-DHM to take into account the water stored by various water ponds in the basin; iv) To couple WEB-DHM with AOGCMs ensembles to elucidate the hydrological effects of anticipated climate change in the basin.

WEB-DHM is a comprehensive and robust model developed by coupling a simple biosphere model 2 (SiB2)[6] and geomorphology-based hydrological model (GBHM)[7]. The model structure permits to incorporate additional hydrological modules to address all major processes in the basin hydrological cycle over a range of space-time scales and climates. The model is capable for long-term continuous simulation of hydrological processes without any intermediate tuning and can simulate floods, low flow and other aspects of hydrological cycle very well. The model has been comprehensively evaluated in both humid and semi-arid basins[8]. For this reason, WEB-DHM model was set up to examine hydrological impact of climate change in terms of flood and drought trends in the basin. The pond function was introduced in the WEB-DHM to consider the amount of water captured by various multipurpose ponds in the basin. From the hydrological point of view, even the ponds influence on river discharge is not significant but the water captured by ponds is utilized for domestic, livestock and agriculture purpose. Also, in addition to hydrological cycle simulation, we can consider integration of crop model and developed hydrological model to simulate crop water use and crop yield. The ponds store water as pre designed capacity and release the extra water. To enhance the level of confidence of model performance, Web-DHM performance was not only evaluated for river runoff but also for soil moisture. However, soil moisture data was not available for the investigated watershed. Surface soil moisture assimilated by LDAS-UT was utilized to supplement validation of WEB-DHM simulated soil moisture. WEB-DHM has ability to directly couple with AOGCMs or RCMs to project climate variables at the basin scale. To achieve this target, hydro-meteorological parameters (rainfall, temperature, shortwave and longwave radiation) from four selected AOGCMs from the coupled Model Inter-comparison Project phase 3 (CMIP3) dataset were processed for climate change impact assessment. For hydrological prediction, AOGCMs output (especially precipitation) is needed to be well bias corrected. For precipitation, bias correction of extreme rain days, normal and no rain days, and seasonal pattern was performed in three steps. WEB-DHM was derived with bias corrected AOGCMs ensembles for past (1981-2000) and future (2046-2065) to predict flood and drought. Flood trends were analyzed based on 10th percentile, top twenty extreme events during twenty years. For drought analysis, low flow trends were used to determine drought discharge. The paper makes contribution to construct comprehensive WEB-DHM model to delineate the impact of climate change in the poorly gauged basin to deliver usable information for water resources management and decision making.

2. STUDY AREA

Soan River, Pakistan, an important river of Pothohar region, originates in the foothills of Muree. Soan River flows from east to the west and after crossing the region in the north and in the middle respectively; falls in the Indus River[9]. The drainage area of the Soan River at Dhok Pathan comprises approximately 6487 km^2. In Soan River basin, agriculture is dependent on 750-1400 mm rainfall and on the rainwater storage ponds. The climate of the basin is monsoon driven with a wet season from July to September

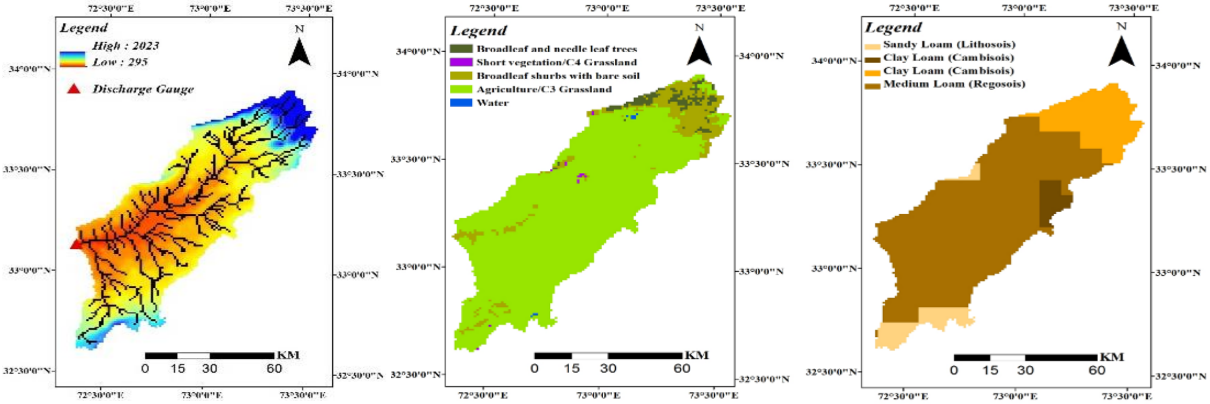
3. METHODOLOGY

3.1 Model

Web-DHM model can give consistent descriptions of water, energy and CO$_2$ fluxes at a basin scale. WEB-DHM model structure is illustrated as follows; a digital elevation model (DEM) is used to define the target area and then the target basin is divided into sub basins using Pfafstetter scheme. Within a given sub basin, each sub-basin is divided into a number of flow intervals considering flow distance to its outlet. Each flow interval includes several model grids. For each model grid with one combination of land use type and soil type, the SiB2 is used to calculate turbulent fluxes between the atmosphere and land surface independently. Each model grid is subdivided into a number of geometrically symmetrical hill slopes, which are the basic hydrological units (BHUs) of the WEB-DHM. For each BHU, the GBHM is used to simulate lateral water redistributions and to calculate runoff. For simplicity, the streams located in one flow interval are lumped into a single virtual channel in the shape of a trapezoid. All flow intervals are linked by the river network generated from the DEM. All runoff from the model grids in the given flow interval is accumulated into the virtual channel and led to the outlet of the river basin. The model was calibrated at the Dhoke Pathan gauge by comparing simulated daily discharges with observed discharge.

3.2 Model Input

Rainfall is unevenly distributed over the basin, both spatially and temporally. To overcome the sparse local network, the APHRODITE daily gridded precipitation (0.25 degree) dataset from 1981-2000 was used. The meteorological forcing datasets (downward shortwave radiation and longwave radiation, U and V components of wind speed, specific humidity, air temperature, atmospheric pressure) for the basin were processed from the Japan Reanalysis Data (JRA-25).



(a) (b) (c)

Fig. 1 Soan River Basin: a) DEM; b) Land use; c) Soil type

Inverse distance weighting technique was applied to interpolate the APHRODITE and AOGCMs data. The digital elevation map was based on the 90-m Shuttle Radar Topographic Mission (SRTM) Digital Elevation Database V4.1. A resampled grid of 1000 m resolution is employed as the computation grid. The vegetation static parameters were defined following Sellers et al. (1996b)[10] by using USGS land use data. Advanced Very High Resolution Radiometer (AVHRR) monthly Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) data set and Moderate Resolution Imaging Spectroradiometer (MODIS-MOD15A2) global LAI and FPAR data sets with 1-km spatial resolution were used. Soil hydraulic characteristics were obtained from the Food and Agriculture Organization (FAO) global dataset (with a spatial resolution of 5 arc minutes). This data included saturated soil-moisture content, residual soil-moisture content, saturated hydrologic conductivity for soil surface, and van Genuchten parameters[11]. The graphical representation of DEM, land use and soil type is depicted in figure 1.

3.3 GCM Model Selection

Twenty four AOGCMs from the CMIP3 dataset were evaluated by using Data Integration and Analysis System (DIAS) of The University of Tokyo, Japan, model selection and data dissemination platform. To select AOGCMs which can reproduce the seasonal evolution of the Asian Summer Monsoon in the base-line period over investigated area, we applied criteria based on spatial correlation (Scorr) and the least root mean square error (RMSE) of climatologically key parameters such as precipitation, air temperature, outgoing long wave radiation and on a more regional scale sea surface temperature, sea level pressure, zonal wind and meridional wind. Scorr is performed to examine how much parameters are correlated with the reference data and RMSE inform about the trend difference from the reference data. An index counter based on criteria (if Scorr > Scorrmean, index = 1, else index = 0) and the root mean square error (if RMSE < RMSEmean, index = 1, else index = 0) is applied to identify the AOGCMs showing good correlation in the investigated area[12]. From suit of twenty four models, four AOGCMs; gfdl_cm2_0, gfdl_cm2_1, miroc3_2_medres and miroc3_2_hires with high index value were selected to direct the range of future projected changes. SRESA1B[13] climate scenario for climate predictions is used for this study.

3.4 Bias Correction

Downscaling of climate data is required to link AOGCMs projections to hydrological model. Statistical or dynamics downscaling is proved to be a useful tool to bridge the scale gap. An improved three step statistical bias correction method was applied to correct precipitation. First, truncation in terms of rain or no rain days using cumulative ranking of the no rain days from observed data which is translated on the ranking; second, fitting of a monthly factor using the observed climatologically average and lastly, the extreme value correction by plotting position of the highest values for each year considered[14].

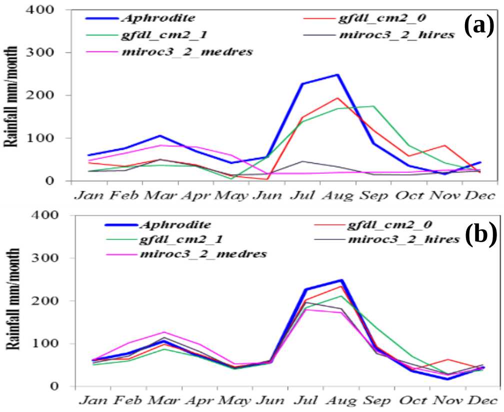


Fig. 2 Seasonal cycle of precipitation during1981-2000; (a) before bias correction, and (b) after the bias correction

Bias correction of selected GCMs precipitation data set is based on the premise that the past is a reasonable guide to the future. In figure 2-a, the selected AOGCMs underestimate in wet and dry season before correction; however, after bias correction the bias was minimized (figure 2-b). It is notable that temperature, down-welling shortwave and longwave radiation was not basis corrected.

3.5 Land Data Assimilation System (LDAS-UT)

LDAS-UT consists of a land surface model (LSM) used to calculate fluxes and soil moisture, a radiative transfer model (RTM) to estimate microwave brightness temperature from surface temperature and soil moisture, and utilizing an optimization scheme to determine optimal values of parameters and surface soil moisture by minimizing the difference between modeled and observed brightness temperature[15]. The comparison was made between WEB-DHM simulated soil moisture and soil moisture output by LDAS-UT to lend credibility to the WEB-DHM simulated results.

4. RESULTS AND DISCUSSIONS

4.1 River Discharge: Calibration and Validation

The model calibration was performed by comparing simulated discharge with the daily inflow at Dhoke Pathan gauge for the year 1997 and validated for the year 1998 as presented in figure 3. The simulated discharge represents the seasonal variation but the voluminous error is noticed for the rainy season. For the year 1997, the NS was found to be 0.80 and RE was 39%. In case of the year 1998, the NS and RE was 0.50 and 48% respectively. The deficiency between the observed and simulated discharge is due to several sources of uncertainties in the model simulation. The contrasting topography and climatic characteristics within the basin demonstrate the high variability of the river regimes among different sub-basins. Lack of available data in the basin, such as outflow of small dams, detailed description of ponds, sparse distribution of precipitation monitoring network, inconsistency in observed discharge data and simplification in the temporal downscaling of daily to hourly rainfall made evaluation of model performance difficult. Moreover, global datasets used in the study are not well representative of local conditions in the basin and are the source of error. However, the model successfully captured the discharge pattern, low flows and peaks. With limited available data and being a poorly gauge basin, the model efficiency is considered satisfactory. The model can be successfully applied to explore the impact of climate change in the in the area of interest.

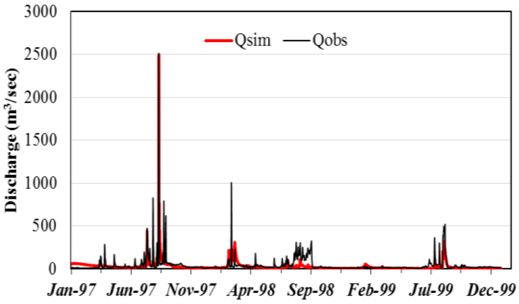


Fig. 3 Comparison of simulated and observed discharge at Dhok Pathan gauge

4.2 Comparison of Soil Moisture outputs

To examine the ability of WEB-DHM to simulate soil moisture at the basin, the daily volumetric soil moisture (m^3/m^3) output of WEB-DHM and LDAS-UT were compared as demonstrated in figure 4. WEB-DHM and LDAS-UT are two different models. In LDAS-UT, SiB2 is used to calculate surface fluxes and soil moisture for each time step. However, in Web-DHM HydroSiB2 is used. WEB-DHM simulated basin average soil moisture is compared with LDAS-UT grid (25kmx25km) based estimation. LDAS-UT grids inside the basin was averaged to represent basin average value. The soil moisture evaluation showed that the Web-DHM predicted volumetric soil moisture pattern is found to be in agreement with the volumetric soil moisture pattern assimilated by LDAS-UT, which is result of land data assimilation using microwave remotely sensed data. To show agreement between soil moisture patterns, the correlation coefficient R^2 is applied ($R^2=0.78$). In the absence of observed data, LDAS-UT can be successfully applied to validate the soil moisture at the basin scale. We presented evidence that WEB-DHM is a useful tool for continuous hydrological simulations at basin scale. The prime purpose of comparison was to evaluate the capability of WEB-DHM to simulate other hydrological parameters such as soil moisture. Coupled with AOGCMs, WEB-DHM can also simulate soil moisture patterns during past and future. However; climate change impact assessment on soil moisture is out of scope of present study.

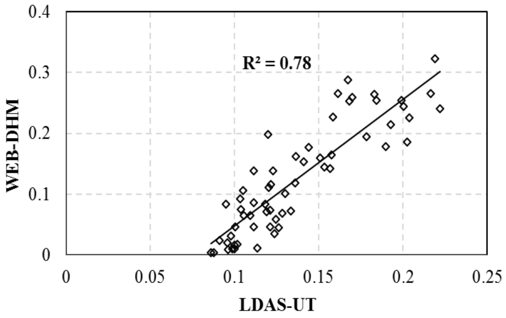


Fig. 4 Comparison of basin average daily surface soil moisture from LDAS-UT and WEB-DHM

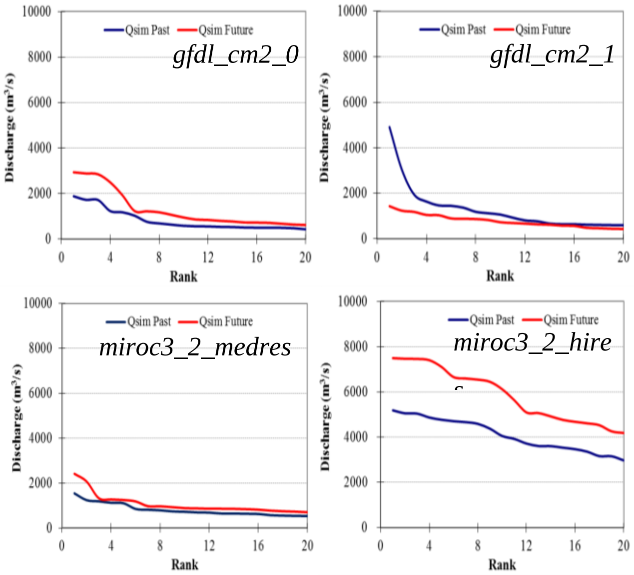


Fig. 5 Climate trends of the top 20 peak discharges during 20 years for past and future

4.3 Peak Flow Trend

Statistically downscaled AOGCMs ensembles was used as input in the model to observe the behavior of discharge during past (1981-2000) and future (2046-2065). The simulated future river flow provided reliable estimation of nature of future extreme events under a non-stationary climate. To estimate peak flow trends during past and future, we performed extreme value analysis based on yearly maxima of twenty (20) years daily discharge of four selected AOGCMs models. Peak flow trends can represent the future floods under the assumption that climatology will be similar in the past and in the future. AOGCMs produced different range of predictions during the future period. The top twenty extreme events were figured for past and future to uncover the effects of climate change on floods in the target basin. Simulated trends indicated that three AOGCMs (gfdl_cm2_0, miroc3_2_medres and miroc3_2_hires) have shown similar trends with substantial increase in magnitude of peak discharges in the future as illustrated in figure 5. However; gfdl_cm2_0 has shown deviation from the aforementioned AOGCMs with decrease in peak discharge in the future. According to the IPCC Fourth Assessment Report criteria for likelihood scale[16], our analysis predicted that it is likely that floods will increase with high magnitude in future in the basin.

4.4 Drought Trends

Drought as a natural phenomenon represents long periods of lower natural water availability and it is incorporated in the climate variability of an area[17]. Drought is source of concern in semi-arid Pakistan due to agrarian nature of country's economy. A key question is whether country will suffer more or less drought in the future. To address this issue, low flow trends were used to determine drought trends owing to climate change. Low flow trends were determined by ranking daily discharge in descending order for each year during past twenty years (1981-2000) and future twenty years (2046-2065). The 364th rank of the past and future climatologically daily discharge simulations, arranged in descending order, was considered as the basis of drought discharge (DD). Average of DD for twenty year past and twenty year future is termed as past DDavg and future DDavg respectively. Four indices defined to examine the climate change impact on drought in the basin as follow; i) Drought discharge average (DDavg) for twenty years, ii) Average number of days during twenty years below DDavg is used as a basis to characterize how frequent the daily discharge for the past twenty years goes below past DDavg and in the future twenty years goes below future DDavg, iii) Maximal drought discharge during twenty years to depict the extent of drought discharge in the past and future, iv) Longest number of days per year when daily discharge was less than past and future DD was identified. Results for drought analysis were not found consistent for all selected AOGCMs as tabulated in Table 1. The values marked as red color represent increase in drought in the future as compared to past. Three AOGCMs (gfdl_cm2_0, gfdl_cm2_1 and miroc3_2_medres) predicted slight decrease in DDavg in the future showing more intense drought in the future as compared to past. Two models (gfdl_cm2_1 and miroc3_2_medres) have shown increase in occurrence of number of days with discharge below DDavg in the future. Also, the three AOGCMs (gfdl_cm2_0, gfdl_cm2_1 and miroc3_2_medres) projected decrease in upper limit of drought discharge in the future. Moreover, two models have shown decrease and two models have predicted increase in longest number of days per year below DDavg. Based on the statistical analysis, it is about as likely as not that the drought will intensify in the future; however, the number of drought days are uncertain.

5. CONCLUSIONS

Water resources assessment is essential prerequisite for sustainable water resources planning and management. The physical based hydrological model supported by global hydro-metrological datasets proved to be an effective tool to predict hydrology of the poorly gauged basin. The model provided reliable estimation of river discharge; however, some discrepancies have been observed in the river discharge simulation during rainy season.

Table 1 Drought trends in Soan River Basin

Models	***Drought Discharge Average (DDavg) for twenty years (m^3/sec)***		***Average no. of Days during twenty years below DDavg***		***Maximum Drought Discharge during twenty years (m^3/sec)***		***Longest # of days per year below DDavg***	
	Past	Future	Past	Future	Past	Future	Past	Future
gfdl_cm2_0	8.01	5.23	120	43	22.78	9.73	271	177
gfdl_cm2_1	8.07	7.54	109	116	22.46	22.07	357	354
miroc3_2_medres	8.75	7.50	123	125	25.86	22.13	315	344
miroc3_2_hires	7.03	7.23	120	119	21.52	21.98	287	309

The lack of data availability hinders high degree of accuracy in prediction of hydrological parameters in the basin. LDAS-UT is applied to obtain surface soil moisture for validation of Web-DHM simulated soil moisture. The ensemble of simulations allows for better understanding the hydrological risks expected to occur due to changing climate. WEB-DHM has shown good performance in simulating long-term continuous hydrological processes. Despite acknowledged data limitations and uncertainties, our analysis suggested that it is likely that floods will occur more with relatively high peak discharges in the future. It is about as likely as not that the drought will intensify in the future; however, the occurrence of number of drought days in the coming decades is uncertain and prevent to predict firm conclusion. The finding of the research underline the need to thoroughly explore the consequences of climate change on floods behavior and droughts by coupling hydrological model with socio-economic model to ensure water and food security in the country. The paper demonstrate an example for estimating hydrological responses at the investigated basin to mitigate the onsets of expected future climate change. The model application on other poorly gauged or ungauged basins is promising.

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