ASSESSING THE RELIABILITY OF WATER YIELD OF A RIVER BASIN

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ABSTRACT

The availability of water in the river basin determines the design, operation and management of water resources projects, such as water supply, sewage disposal, irrigation and hydropower, in that vicinity. The major hydrological term that can well describe the capacity of a river basin to satisfy these demands is the flow duration curve, which is derived from long-term records of the river flow. The physiographic characteristics of the basin and climatic inputs might not be static during flow measurement and for the lifetime of the proposed projects. Land use change in terms of urbanization, wetland reclamation, agricultural intensification, deforestation, etc. and climate change due to enhanced emissions of greenhouse gases are receiving considerable attention as the main factors affecting the water yield of river basins, and hence their flow duration curves. The current study carried out in the river Fergus presents a method that employs hydrological modeling and statistical tests to detect any significant land use change which can alter the dynamics of the basin. The rainfall and temperature changes predicted by GCM integrations are transferred to basin scenarios of rainfall and evapotranspiration using statistical downscaling techniques. Thus, stochastic rainfall and evaporation models are used to generate continuous future climatic inputs to the rainfall-runoff model. The impact of climate change on the flow duration curve (water yield) is investigated through a continuous simulation experiment organized from the statistical downscaling algorithm, the weather generating models and a rainfall-runoff conceptual model. The reliability of the conventionally estimated flow duration curve is then discussed.

Key words: *flow duration curve; statistical downscaling; climate scenarios; stochastic model; conceptual model*

1. INTRODUCTION

The major uncertainty in water resources management is the variability of water supply and demand pertaining to changes in climatic variables and in dynamics of river basins. It is well understood that the climate is changing in response to enhanced emissions of greenhouse gases and aerosols; and consequently precipitation and temperature, along with other climatic variables, are showing a significant shift from the usual trend as predicted by the Global Circulation Models (GCMs). Human activities within a river basin, such as urbanization, wetland reclamation, deforestation, agricultural intensification, road construction, etc., will alter the way the basin responds to such climatic inputs. The water supply potential of a river basin is therefore sensitive to land use and climate changes. Rapid population growth, economic development and temperature rise are also expected to put extra pressure on demand for water, which is not addressed in this paper.

In the planning, design and management of water resource projects, the amount of streamflow exceeded for a given percentage of time is commonly used to quantify the surface water supply potential available in the river basin. The relationship between streamflow and the percentage of time it is exceeded is known as a flow duration curve. Therefore, the water yield of a river basin can be determined from its flow duration curve. Moreover, the shape of the flow duration curve explains the river basin's characteristic response to its average climatic inputs. A very steep slope curve at the high-flow end results from a highly variable flow with little surface storage in lakes and swamps; and a very flat slope at the low-flow end shows that the groundwater contribution is dominant (Gordon et. al., 1995). Hence, the flow duration curve is probably the most appropriate hydrological parameter for the study of water yield variability associated with both land use and climate changes.

The GCMs are predicting future climate scenarios from forecasts of emission levels, population growth, and of social, economical, and cultural developments. But these predictions are at a very coarse spatial resolution and some of the variables are not well simulated. For the purpose of hydrological impact assessment, these climate scenarios have to be statistical downscaled to river basin level (Kilsby et. al., 1999). After the effect of land use change on observed flow series is ruled out, a continuous simulation experiment is carried out to investigate the impact of climate change on flow duration curves.

2. THE STUDY AREA AND DATA SETS

The current study was conducted on Fergus river catchment at Ballycorey in County Clare, Ireland. The annual mean rainfall over the catchment is 1425 mm and its annual daily mean flow from 512 km^2 drainage area is 10.25 m^3/s. The catchment is dominantly karstic with small caves, scattered ponds and minor lakes. The land use and land cover pattern of the catchment comprises of farmland, scrubland, and woodland; and the Burren National Park is located within this catchment.

Areal mean daily rainfall data is assembled from rainfall records at four meteorological stations within the catchment and daily mean flow data at the outlet is also collected for the period of 1975-1999. Monthly potential evapotranspiration and daily mean temperature are adapted from the nearby Shannon Airport and Birr synoptic stations respectively. Sunshine hours, wind speed and relative humidity for the reference climate time (1961-1990) are obtained from the Met Eireann web site.

The NCEP/NCAR Reanalysis project assimilates daily and six-hourly climate data at different atmospheric levels and at spatial scale of 2.5^0 x 2.5^0 from observations and forecast systems. The daily NCEP/NCAR reanalysis data for selected variables has been downloaded from the online service for the years 1958-2001. Monthly mean climate predictions for 1950-2099 from the recent Hadley Climate Center GCM (HadCM3) for both SRES A2 and SRES B2 emission scenarios have been accessed from the IPCC Data Distribution Center ftp database by request. The spatial resolution of the HadCM3 GCM is 2.5^0 Latitude by 3.75^0 Longitude.

3. SURFACE CLIMATE VARIABLES MODELING

The water yield of a river basin depends on the relative proportion of water in the components of the hydrologic cycle within that basin. The basin receives water from the atmosphere as precipitation and gives back some part of it in the form of evapotranspiration. The balance between these major climate variables at surface level determines the basin yield in the form of streamflow and groundwater resources. Therefore, accurate representation of evapotranspiration and rainfall series is essential for meaningful and tangible climate impact assessment on water yield.

3.1. Evapotranspiration series modeling

The rate of evapotranspiration depends on the amounts of moisture and energy available to initiate and transport vapors. However, monthly variations of long-term relative humidity and winds in the study area are relatively small as compared with the range of these variables given in FAO Report 24 (Doorenbos and Pruitt, 1992). Therefore, the temperature-based estimation method can be used to disaggregate monthly evapotranspiration into daily series and to derive evapotranspiration scenario from that of temperature. The Blanney-Criddle method with some modification is given by:

$$PE_i = c\left[p_i\left(0.46T + 8\right)\right] + b \qquad (1)$$

where, PE_i is the mean daily potential evapotranspiration in mm/day over a month, T is the mean daily temperature in ^{o}C over a month, p_i is the mean daily percentage of total annual sunshine hours for month i, c is an adjustment factor which depends on minimum relative humidity and daytime wind estimates, and b is a regression correction factor. The two parameters, c and b, are estimated by least square solution and the performance of the model is shown in Figure 1.

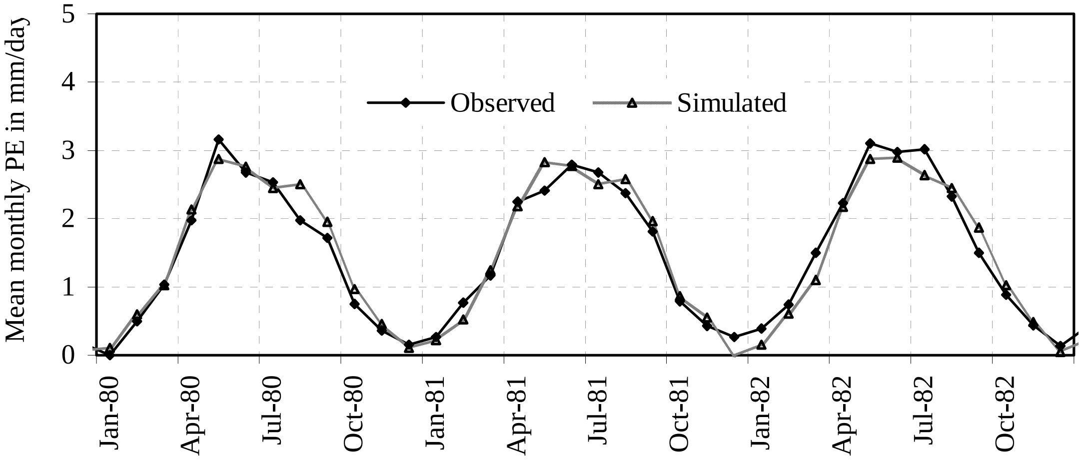


Figure 1. Comparison of observed and simulated mean monthly potential evapotranspiration.

While the autocorrelation function of the daily mean evapotranspiration series for each month decayed exponentially, the partial autocorrelation function cut off after lag-one. This suggests that a first order autoregressive process would suffice to model the series. Hence, the evapotranspiration series model can be expressed as:

$$(1-\rho_1 B)\cdot(PE_t-\mu_{PE})=\sqrt{\left(1-\rho_1^2\right)}\cdot\sigma_{PE}\cdot\xi_t \tag{2}$$

where, μ_{PE} is monthly mean PE_t, σ_{PE} is its standard deviation, ρ_1 is lag-1 autocorrelation coefficient, B is the backward shift operator, and ξ_t is the standard normal ordinate. The first three symbols defined above are parameters of the model and statistically determined from the daily mean series for all the twelve months.

3.2. Stochastic rainfall modeling

Rainfall series observed at meteorological stations portray randomness both in amount and in time of occurrence. When a rainfall-generating mechanism, such as low-pressure centers and/or warm fronts, passes over a certain area, rainstorms that comprise clusters of rain cells falls on the ground. These clusters of rain cells within rainstorms characterize both the magnitude and occurrence of the rainfall. Thus, physically possible representation of the rainfall process can be achieved through cluster point process models. Among such models, the Modified Bartlett-Lewis Rectangular Pulses Model (MBLRPM) performs well in Ireland (Khaliq, 1995; Khaliq and Cunnane, 1996). These references have detailed descriptions and analytical expressions of the model. The MBLRP model has six parameters.

Monthly estimates of mean, variance, lag-1 autocorrelation and dry proportion at 1-day and 2-days levels of aggregations of the areal mean daily rainfall series and the respective analytical expressions of the model are used for parameter estimation. A weighted least square objective function and Rosenbrock's non-linear unconstrained algorithm are used for optimization. For the purpose of validation of the estimated parameters, the model's ability in reproducing properties that are not used during calibration is checked. Figure 2 displays one of such properties used for validation.

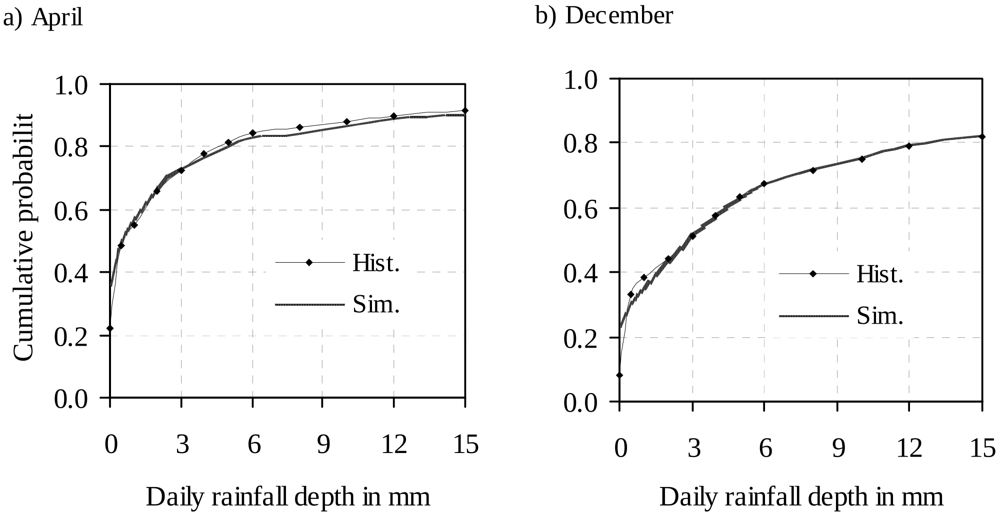


Figure 2. Cumulative rainfall depth distribution for both historical and MBLRPM simulated daily rainfall series.

4. INVESTIGATION OF LAND USE CHANGE THROUGH HYDROLOGICAL MODELING AND STATISTICAL TESTING

Before examining the effect of climate change it is necessary to establish whether any effects of land use change on the flow regime could be detected. The hydrological response of river basins to climatic inputs is highly dependent on the current state of the basins' characteristics. When parts of such dynamic elements of the basin are significantly changing due to human activities, it might respond differently to climatic inputs. For example, afforestation will cause interception of more rainfall during wet seasons and transpiration of more water during dry seasons, which results in depletion of downstream water yields. The reverse will happen in the case of deforestation. Wetland drainage lowers the water table and creates soil moisture stress. This reduces rate of evapotranspiration and consequently increases dry season flows. Intensive agricultural practices, urbanization and road construction have their own effect on flow regimes. It is essential to know whether the observed changes are significant enough to alter the flow regime or not. In this section, conceptual rainfall-runoff model and statistical test will be employed to detect if the land-use has significantly changed in a way to affect annual water yield. Then, the flow duration curves of the observed and model simulated flows will be compared.

4.1. Conceptual rainfall-runoff modeling

The purpose of the conceptual rainfall-runoff model in this study is to filter out the impact of climate change in the flow regime. Since climatic variables, rainfall and evapotranspiration, are inputs to the model, model-derived flow residuals are believed to be free from climate change effects. By model residuals we mean the difference between the observed and model simulated flow series. Model selection relies on available sets of data, computational effort and the scale of the intended job. A lumped conceptual rainfall-runoff model known as Soil Moisture Accounting and Routing with Groundwater component (SMARG) is sufficient enough to represent daily rainfall-runoff process for the purpose of impact assessment. The model has gone through a number of improvement stages since 1970. Its developmental stages and full descriptions can be found in O'Connel et. al. (1970), Khan (1986) and Liang (1992). The Windows version of the model is available in the former UCGMODEL package as well as in the recently revised GFFS software. Its performance in such a wet climate is very reliable. The SMARG model has six water balance parameters and three flow routing parameters.

The synchronous data series records are divided in to reference and test periods. The reference period should be as small as possible so that appreciable land use change would not have occurred within it, and it should be long enough to properly calibrate and verify the model and to enhance the discriminating power of the statistical test. Accordingly the earliest five years (1975-1979) are used as reference periods and the SMARG is calibrated with the first three years and verified with the last two years of the reference period. The model R^2 efficiency criterion during calibration and verification is found to be 92.83% and 91.67% respectively. Then flow series is simulated for other periods (1980-1999). We referred this as a ‘forward’ simulation since it proceeds from the earlier to the later years.

In order to account for model uncertainties and systematic errors in the data series, a ‘backward’ simulation in which the reference period is moved to the latest years (1995-1999) and the earliest years (1975-1994) are used as test periods. Now the SMARG is calibrated with 1995, 1996 and 1997 data series and verified with 1998 and 1999 data series. The R^2 efficient criterion of 95.45% and 96.10% is obtained during calibration and verification respectively. Using the parameters derived in the reference period, flow series is simulated for earlier years.

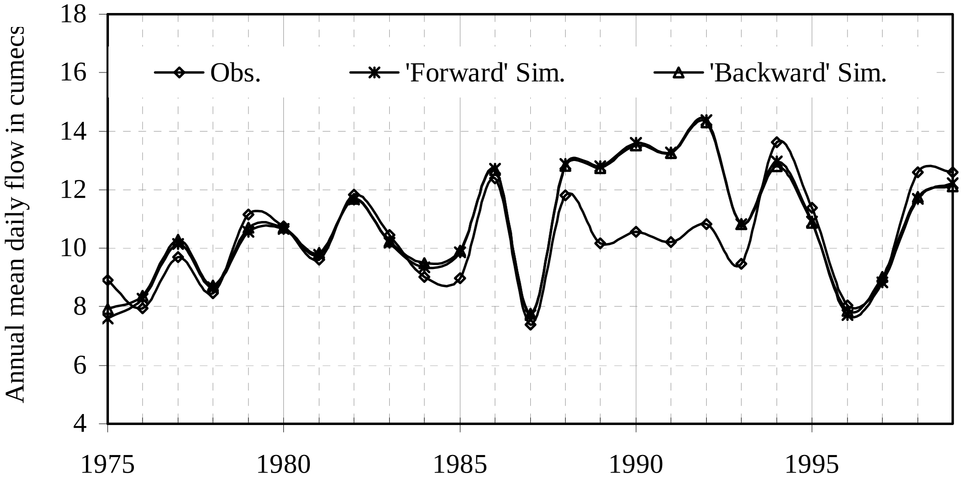


Figure 3. Comparison of the observed, ‘forward’ and ‘backward’ simulated annual mean daily flows.

Graphical comparison displayed in Figure 3 reveal that both simulated series are close to each other during all years of the test periods. But the observed series deviates from both simulated series in the years of 1989-1992. The following sections will undertake further analysis using statistical test and flow duration curves, after which conclusions about this deviation will be provided.

4.2. Statistical test

Impact of land use change on flow regime can be detected using either monotonic trend test or test for shift depending on the nature of land use change and on the length of the data series (Lorup et. al., 1998). The test for shift is chosen for the present study as the data series are not long enough and the extent of land use change is not well known. In the previous section we defined a reference period of five years and the remaining twenty years are classified into five test periods of five years long for both ‘forward’ and ‘backward’ simulations. Annual mean daily flow can indicate the basin water yield, and hence the annual mean daily flow residual is selected as a test variable.

A non-parametric Wilcoxon Rank-Sum test is very efficient in detecting shift in data pairs with a small number of data points without making any assumption about distribution type. The test is applied on paired samples of the reference period and one test period at a time for both simulations.

The ‘forward’ simulation test accepted the null hypothesis, which states the means of the test variables are the same in the reference and test periods, at 0.05 levels of significance for all periods considered. But the ‘backward’ simulation test rejected it for period 3. As it can be observed from Figure 3, some years in periods 3 and 4 are behaving differently. Therefore, a test period that consists these years (1989-1992) is organized and tested for a shift. Both ‘forward’ and ‘backward’ simulation tests rejected similarity in means of the observed and simulated statistics. But the annual mean daily flows of the two simulations are almost the same. Such discrepancy might happen due to systematic errors in the data series, particularly in the areal mean daily rainfall. Another source could be a land use change that recovered within four years.

4.3. Flow duration curves

The statistical test was carried out on annual statistics of the flow residual series. However, land use change can affect dry and wet season flows in such a way that the annual yield will remain the same. Flow duration curves can indicate seasonal variation of flow and stream yield available at any specified percentage of time. Comparison of the observed and SMARG simulated flow duration curves will provide enough evidence about any change or inconsistency in flow regime. Daily mean flow duration curves for the median years are prepared from the daily observed and simulated flow series for all periods. Period 1 (1975-1979) and Period 5 (1995-1999) are reference periods in which the SMARG model is calibrated and verified. So, it is enough to display the plot of flow duration curves for Period 2 and the worst years between Periods 3 and 4 in Figure 4.

The observed and simulated flow duration curves for the period of 1989-1992 are quite different as shown in Figure 4b. But the two simulated flow duration curves are almost the same. For all other periods, both ‘forward’ and ‘backward’ simulations reproduced the observed flow duration curves satisfactorily, see Figure 4a. The hydrological modeling, the statistical test and the flow duration curves are indicating that the period of 1989-1992 is significantly different from both earlier and latter periods. As speculated earlier, this might be due to systematic errors in the data series or due to recovered land use change. Therefore, it is decided to discard the data series in this period from further analysis.

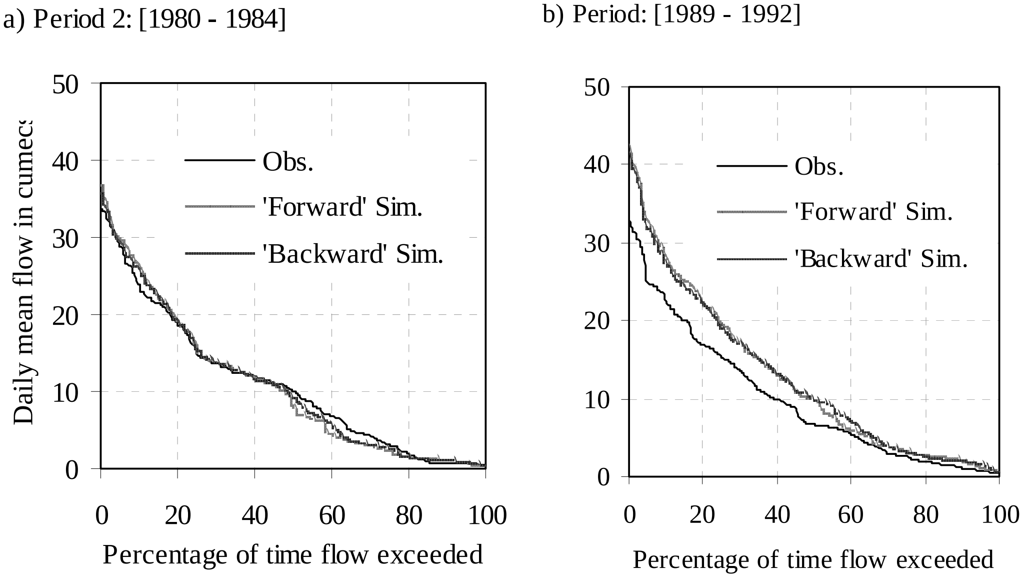


Figure 4. Daily mean flow duration curves of a median year of the observed and simulated flow series for different periods.

For simulation and analysis work in succeeding sections, the SMARG model is calibrated with the 1975-1988 data series and verified with the 1993-1999 data series. The corrupted part of the data series has been omitted between the calibration and the verification series. The model's R^2 efficiency for these sets is found to be 93.62% and 95.32% for calibration and verification respectively.

5. STATISTICAL DOWNSCALING OF GCM OUTPUTS INTO A RIVER BASIN CLIMATE PROCESS

The state-of-the-art GCM predictions of surface climate variables are not dependable at least for two main reasons. Firstly, the spatial resolution of GCMs is far greater than the scale at which hydrological processes are operating at river basins. The second problem is the variability of some of the surface climate variables, like cloud cover and precipitation are not well reproduced even at those coarser scales. However, GCM simulations are providing very important information about future average trends in climate variables. This information along with observed climate variability could be systematically utilized for hydrological impact assessment. Empirical relationship between atmospheric circulation variables and surface climate statistics, which is commonly known as statistical downscaling, transfers climate scenarios forecasted by GCM to river basin scenarios. After some plausible assumptions, the basin climate scenarios can be represented in the stochastic processes of the respective climate variables.

5.1. Development of river basin scenarios

The two main climate variables at a river basin are rainfall and temperature. The river basin climate scenarios can be expressed as monthly changes in mean rainfall depth, in rainfall occurrence (dry proportion), and in mean temperature. Statistical downscaling relationship between these three observed statistics and atmospheric circulation variables derived from NCEP/NCAR reanalysis data is the one that transfers HadCM3 scenarios to basin scenarios, given that the same relationship holds during climate enhancement. The NCEP/NCAR reanalysis data are regridded to meet the HadCM3 grid size by simple interpolation. Then, relevant atmospheric circulation variables are selected and derived at a grid center (52.5N, 7.5W) close to the Fergus river basin.

Correlation analysis conducted on monthly values of both surface and atmospheric variables has guided the choice of the most influential predictor variables. Accordingly, geostrophic vorticity at 850 hPa, geostrophic winds at 850 hPa and specific humidity at 500 hPa are selected as uncorrelated predictors for monthly mean rainfall and dry proportion. Predictors considered for monthly mean temperature are meridian thermal wind within 850-500 hPa, geopotential thickness of 850-500 hPa and specific humidity at 500 hPa. The specific humidity is derived from relative humidity and air temperature at a given pressure level.

Monthly multiple regression model and a three layer feed-forward neural networks model are applied to establish a predictand-predictors relationship of the above variables using the 1958-1999 data series. Even if the neural networks model is performing better than the multiple regression model, the latter was adopted since the number of weights of the neural networks became close to the monthly data points and this caused a tendency of over fitting the data series. While the multiple regression models for monthly mean rainfall and dry proportion were found to be statistically significant, the monthly mean temperature model was not. Therefore, the HadCM3 temperature scenarios of the nearby grid point are directly used for the Fergus river basin. The HadCM3 integrations for both SRES A2 and SRES B2 emission scenarios underestimated winter mean temperatures. For this reason, the mean temperature anomalies are adopted as mean temperature scenarios at basin level. Figure 5 displays the effect of downscaling on monthly mean rainfall depth.

The length of the data series available for all variables at Fergus catchment is 25 years. So, we decided to establish climate scenarios for a period of 25 years from the statistically downscaled series. The period coincident with the time of observation (1975-1999) is referred as a reference climate period. The changing factors of the mean rainfall statistics and anomalies of the mean temperature in the subsequent four climate periods of the 21st century relative to the reference climate period are evaluated. The downscaled scenarios (i.e. the changing factors) of dry proportion are not significantly different from unity.

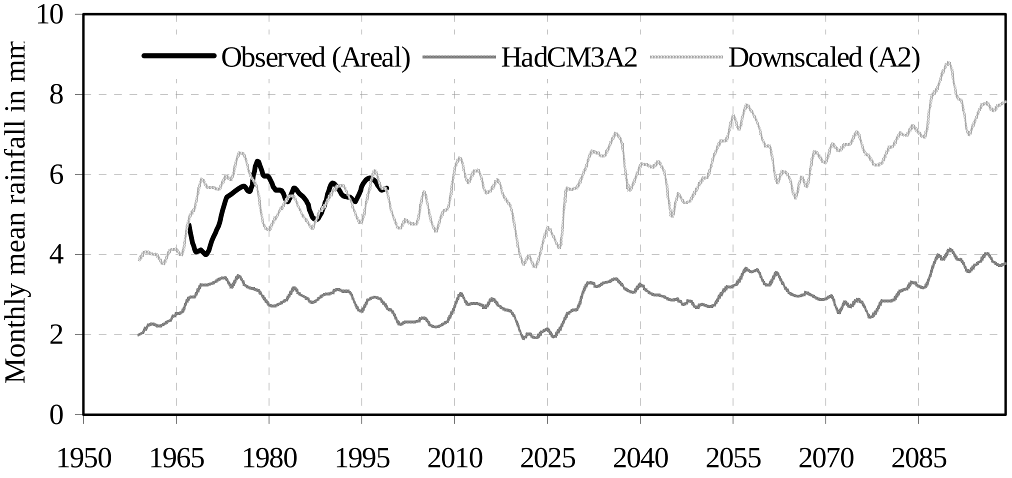
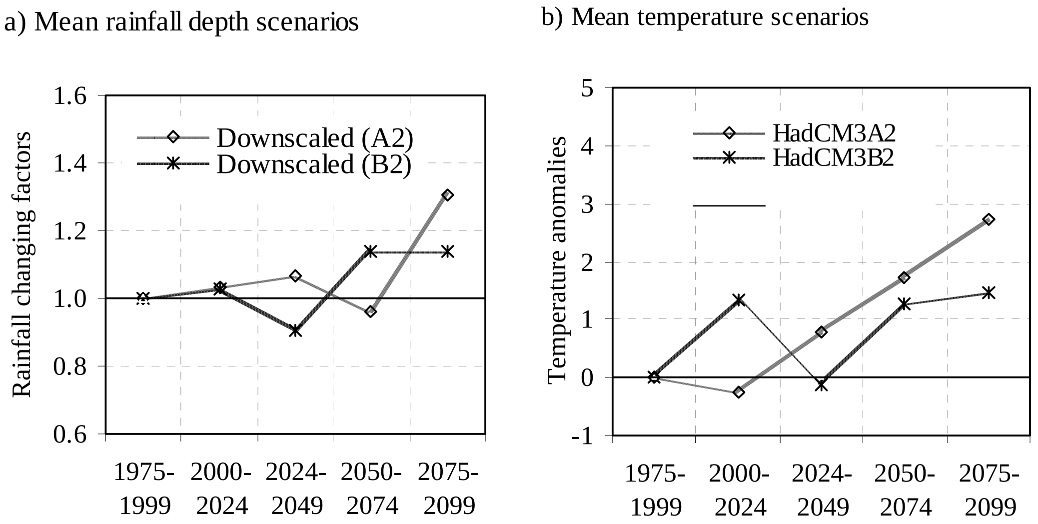


Figure 5. The 10 yrs moving average of mean rainfall depth of the observed series at Fergus catchment, the HadCM3A2 predictions and the corresponding downscaled series for January.

Therefore, the mean dry proportion is assumed to remain the same in future. Samples of mean rainfall depth and mean temperature scenarios established for Fergus catchment are portrayed in Figure 6.


a) Mean rainfall depth scenarios

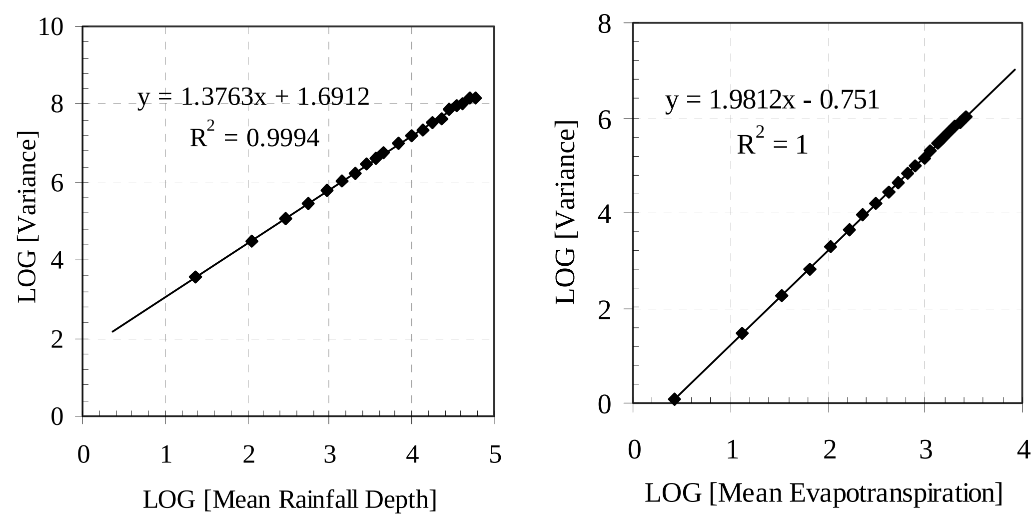
b) Mean temperature scenarios

Figure 6. Mean rainfall depth and temperature scenarios developed for Fergus catchment from SRES A2 and SRES B2 integrations of HadCM3 for January.

5.2. Representing the river basin scenarios into climate variables' process

The river basin climate scenarios derived in the previous section are indicating the rate at which the mean climate of the basin is about to change. In order to introduce variability in the future basin climate time series, the mean rainfall and temperature basin scenarios have to be transferred into parameters of the respective rainfall and evapotranspiration processes. Higher order moments of climate time series are exhibiting a simple scaling property (Burlando and Rosso, 1991). The scaling relationship between variance and mean could be exploited for finding changing factors of the variance from that of the mean. For Fergus catchment, the central moments of the areal mean daily rainfall depth and potential evapotranspiration series have a noticeable scaling relationship as verified in Figure 7. The non-seasonality of the scaling exponents was taken as a sufficient condition to assume the same scaling relationship will hold while the climate is changing.

The mean temperature anomalies are converted into changing factors of the mean potential evapotranspiration using Equation 1 and the observed mean value at the reference climate period. The scaling relationship in Figure 7 enabled us to deduce the scaling factor of the variance from that of the mean. Since the mean of the white noise process of the evapotranspiration model is always zero, the above simple scaling property suggests that the white noise variance will remain constant during climate change. Then, the scaling factor of the lag-1 autocorrelation coefficient is estimated from the scaling factor of the variance using the AR(1) model property that states $\left(1-\rho_1^2\right)\cdot\sigma_{PE}^2=\sigma_a^2$, where the symbols have the meaning given in Equation 2. Therefore, the basin mean evapotranspiration scenarios are transferred to the three model parameters.


a) Daly rainfall depth in mm

b) Daily evapotranspiration in mm

Figure 7. Scaling relationship between central moments at Fergus catchment.

The rainfall model has six parameters and we need six conditions to represent the mean rainfall scenarios in the MBLRP model. Two of the conditions are already known: scaling factors of the mean and the variance. Another most important property of the rainfall depth process is the scale of fluctuation (Vanmarcke, 1983). An assumption of linear transformation from the current to the climate-induced rainfall depth process is sufficient to derive a scaling factor for the scale of fluctuation (Demissie and Cunnane, 2002). Inspired by the classical rainfall intensity-duration relationship, a scaling property between mean rain cell intensity and duration is hypothesized. From the development history of the model, the mean number of cells per rainstorm is assumed to remain the same during climate change. The inverse of the rain cell duration follows a two-parameter gamma distribution. The variability of the cell duration could be achieved by varying the scale parameter and fixing the shape parameter during all climate periods. Then after algebraic rearrangement, a simple non-linear optimization has provided the scaling factors of the MBLRP model parameters from these likely conditions.

6. IMPACT OF CLIMATE CHANGE ON WATER YIELD

Climate impact assessment on hydrological systems requires generation of future climate data series and simulation of these series through a water balance model. Such an approach is usually referred as a continuous simulation experiment. For the purpose of assessing the impact of climate change on flow duration curve (water yield), a continuous simulation scheme is organized from the AR(1) evapotranspiration model, the MBLRP rainfall model, the SMARG watershed model, the statistical downscaling algorithm and a routine that derives daily flow duration curve for a median year.

The rainfall, evapotranspiration and the conceptual watershed models are calibrated and verified with the reference climate period (1975-1999) data series. The statistical downscaling algorithm has transferred GCM predicted climate scenarios of the four climate periods in the 21st century into rainfall and evapotranspiration model parameters. Thousand realizations of rainfall and evapotranspiration series are generated using the perturbed model parameters for all climate periods. These realizations are continuously simulated through the water balance model and an ensemble of daily flow duration curves for median years are derived. The median of the ensemble for the reference climate period with no scenario and for the future climate periods with SRES A2 and SRES B2 scenarios (A2 Sim. and B2 Sim.) are evaluated. The deviation between the reference and the climate-induced flow duration curves indicates how the flow regime would be affected by climate change. It is possible to construct scenarios of daily mean flow of a median year, which is the percentage change of flow from the reference climate period to the future climate period at a specified percentage of time the flow is exceeded. A plot of such scenarios for different percentage of exceedence gives a flow duration curve scenario. From the continuous simulation experiment for the Fergus river catchment, flow duration curve scenarios are developed for both SRES A2 and SRES B2 emission scenarios. Figure 9 presents these scenarios for the climate period of 2075-2099.

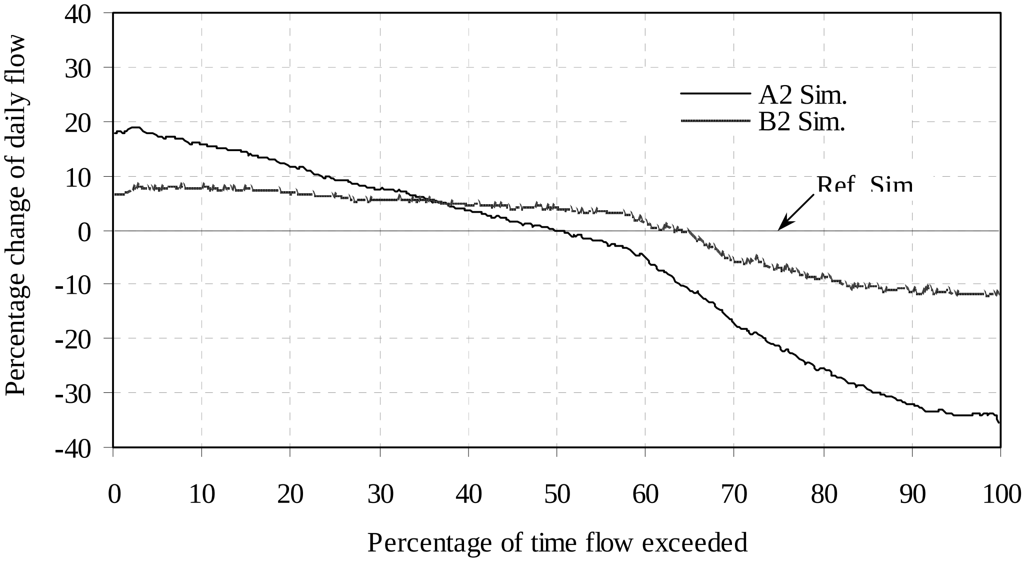


Figure 8. A daily mean flow duration curve scenarios of a median year in the fourth future climate period (2075-2099) for SRES A2 and SRES B2 emission scenarios.

7. DISCUSSION OF RESULTS AND CONCLUSIONS

The results displayed in Figure 8 revealed that the low-flow end of a flow duration curve is highly sensitive to climate change than other flow regimes. This has its own implication on the reliability of water yields estimated from the conventional flow duration curves. It is also evident that climate change has minor effect on flow regime around the mean but the effect becomes very serious as the flow regime moves towards the extremes.

Therefore, the impact of climate change has to be properly considered during planning and design of water resources projects. The water resources management practice has to incorporate prediction of climate impacts in advance and device adaptive strategies.

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