Uncertainty analysis of impact of climate change on hydrology and water resources

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Abstract A procedure for the uncertainty analysis of climate change impact assessment is proposed and analysed by application to two river basins in China. A monthly water balance model was chosen to simulate soil moisture and runoff. Monte Carlo simulation was used to generate different parameter sets, and probability density functions of runoff series were estimated by a nonparametric method. The results of the case study indicate that runoff is more sensitive to variation in precipitation than to increase in temperature; the smaller the runoff coefficient, the larger the uncertainty. At 5% significance level and the most likely climatic scenario (temperature increase of 1°C and rainfall increase by 10%), the future peak flood discharge at Huayuan and Nantang basins in the south of China may increase by 47.41% and 38.16% respectively, which may seriously affect flood protection works and water resources systems.

INTRODUCTION

Global warming or climate variability is expected to alter the timing and magnitude of runoff and soil moisture. As a result it has important implications for the existing hydrological balance and water resources as well as for future water resources planning and management. Quantitative estimation of the hydrological effects of climate change is therefore essential for understanding and solving potential water resource problems that may occur in the future.

General circulation models (GCMs) show a significant global warming as a result of a doubling in CO_2 concentration in the atmosphere. It is anticipated that the mean annual temperature will increase by about 1-2°C. To assess the impact of climate change on hydrology and water resources, a variety of impact assessment techniques or tools have been developed and tested in China. Based on GCM outputs and hypothetical scenarios, the sensitivity of hydrological and water resource system variables to climate change have been investigated in the Dongjiang basin in the south of China (Guo, 1995).

There are uncertainties at all levels in the methodology of a climate change impact assessment. These include the projection of future CO_2 emissions, atmospheric CO_2 concentrations, possible changes in climate, available hydrological data, appropriateness of the model structure, parameter estimation procedures, etc. There are two methods which attempt to account for these uncertainties: scenario analysis and risk analysis. Scenario analysis comprises a set of techniques that anticipate and prepare for the impacts of uncertain future events. It is used here to describe an analysis of the range of uncertainties encountered in an assessment study. The confidence limits are often used as upper, lower and best estimates of an outcome. Risk analysis deals with uncertainty in terms of the risk of impact (Carter *et al.*, 1993).

In this paper a procedure is proposed for assessing the uncertainty of climate change impact analyses. The procedure includes choosing a monthly water balance model to simulate soil moisture and runoff. Monte Carlo simulation is used to generate runoff with different sets of parameters and the probability density functions of runoff are estimated by a nonparametric method. Quantitative estimations of uncertainty of the model parameters and runoff are calculated for different GCM outputs and hypothetical climatic scenarios.

WATER BALANCE MODEL AND HYDROLOGICAL EFFECTS OF CLIMATE CHANGE

Two basins, Nantang and Huayuan, were selected for this study. The Nantang basin lies in the subtropical zone with warm and humid climate, in the Pearl River basin in the Guangdong province, while the Huayuan basin is located in the Hanjiang River basin, the largest tributary of the Yangtze River in the Hubei province. Front-type and typhoon-type rainfall are two important phenomena in these basins with 75% of annual rainfall and runoff occurring in the wet season (April-September). The characteristics of these basins and some sample statistics of the data collected in this study are listed in Table 1, where $\bar{P}$, $\bar{E}$ and $\bar{R}$ represent mean annual precipitation, evaporation and runoff respectively, and $\alpha = \bar{R}/\bar{P}$ is the runoff coefficient.

Table 1 Basin and data characteristics.

Basin	Area (km^2)	Baseline sample	$\bar{P}$ (mm)	$\bar{E}$ (mm)	$\bar{R}$ (mm)	α
Nantang	1080	1966-1988	1630.6	1036.6	849.8	0.521
Huayuan	2601	1964-1987	1113.6	1207.4	364.1	0.327

A monthly water balance model was developed and used in southern China for climatic change impact assessment by the author (Guo, 1995). The same model will be used in this study. It incorporates a soil moisture accounting procedure and a procedure for the estimation of evapotranspiration. It uses readily available hydrometeorological data as well as soil and vegetation characteristics. This model has five parameters, *SMAX*, *C*, *K*, *K*1 and *K*2, where *SMAX* is the maximum soil moisture storage and *C*, *K*1 and *K*2 represent effective surface runoff generation area, interflow and groundwater linear reservoir storage coefficients, respectively. *K* is the ratio of E-601 pan evaporation data to potential evapotranspiration. The model input data are rainfall, evaporation (or meteorological data). The model outputs are runoff and soil moisture content.

The model was calibrated on these basins in which the recorded data were divided into calibration (*Nc*) and verification (*Nv*) periods. Two criteria, model efficiency (R^2) and mean relative error (*RE*), were chosen as objective functions and the Rosenbrock method was used to optimize model parameters (Guo, 1995). The calibrated parameters and simulation results are given in Table 2. In the Nantang basin, the value of R^2 is

Table 2 Model parameters and efficiency in the calibration (Rc^2%) and verification (Rv^2%) periods.

Basin	*K*	*SMAX*	*C*	*K*1	*K*2	Rc^2(%)	Rv^2(%)	*RE*(%)
Nantang	0.85	158.8	0.450	0.200	0.263	90.39	89.6	−0.04
Huayuan	0.67	149.0	0.541	0.244	0.451	88.97	85.0	−0.09

90.39% in the calibration period and 88.97% in the verification period. The relative error *RE* is equal to 0.04% for the full sample. The results indicate that the model is capable of producing both the magnitude and timing of monthly runoff and the soil moisture condition.

The model was then used to simulate monthly runoff and soil moisture for these basins under different climatic conditions. It has been shown previously by the author that the potential evaporation is likely to increase by about 5% per degree Celsius increase in temperature based on the average value of modified Penman, Morton, Budyko and Thornthwaite models (Guo, 1995). The magnitude of changes in runoff and soil moisture induced by the hypothetical scenarios and GCM outputs were also calculated. In the Nantang basin, temperature increases by 1 °C combined with ±10% change in expected precipitation is likely to result in runoff and soil moisture changes from 16.13% to −20.79% and from 2.53% to −10.25% in the dry season (October-March); and from 15.28% to −20.05% and from 0.77% to −2.20%, respectively, in the wet season (April-September).

UNCERTAINTY IN THE ESTIMATION OF MODEL PARAMETERS

The model parameters are generally calibrated from the observed data. The optimum set of chosen parameters minimize the difference between the estimated and the observed runoff. The various uncertainties mentioned previously will be reflected in the calibrated parameters. The uncertainty in the estimation of model parameters implicitly considers the error induced by incorrect model structure, data errors, climatic variation factors, etc.

A common way to quantify the combined effect of parameter uncertainty on model performance is known as first-order reliability analysis. Melching *et al.* (1990) and Harlin *et al.* (1992) have shown that Monte Carlo simulation is one of the most effective ways to study parameter uncertainty. The runoff series at the two basins were divided into several periods for the purpose of studying uncertainty in the estimation of the model parameters. For each period, Rosenbrock optimization method as mentioned above was used to optimize the parameters subject to minimizing mean relative error and maximizing R^2. Table 3 lists the calibration results at the Nantang basin. The average model efficiency is equal to 90.86%, which is very close to the results for the full baseline sample (see Table 2, where R^2 = 90.39%). However, there are some variations in parameters for different calibration periods.

Since the observed data record is not long enough to infer the underlying distribution form for the model parameters, one can make the assumption that the sampling distribu-

Table 3 Model parameters and efficiency at different calibration periods at Nantang basin.

Period	*K*	*SMAX*	*C*	*K*1	*K*2	R^2(%)	*RE*(%)
1966-69	0.775	154.9	0.378	0.134	0.360	89.69	0.02
1970-73	0.870	157.5	0.288	0.262	0.326	88.44	−0.13
1974-77	0.820	142.5	0.231	0.268	0.476	92.29	−0.01
1978-81	0.850	157.0	0.290	0.258	0.375	93.74	0.42
1982-85	0.880	165.0	0.276	0.381	0.335	89.91	0.44
1986-88	0.780	156.8	0.203	0.309	0.371	91.07	0.12
Mean	0.829	155.6	0.278	0.269	0.374	90.86	0.14

Table 4 The statistics of estimated and simulated parameters.

Parameter	Basin	μ	σ	*Cs*
K	Nantang	0.829(0.830)	0.041(0.041)	(0.105)
	Huayuan	0.667(0.668)	0.045(0.045)	(0.106)
SMAX	Nantang	155.6(155.8)	6.676(6.537)	(−0.008)
	Huayuan	149.6(149.7)	5.225(5.116)	(−0.008)
*K*1	Nantang	0.278(0.277)	0.055(0.054)	(0.078)
	Huayuan	0.377(0.381)	0.124(0.122)	(0.079)
*K*2	Nantang	0.269(0.271)	0.074(0.074)	(0.010)
	Huayuan	0.147(0.149)	0.064(0.064)	(0.066)
C	Nantang	0.374(0.375)	0.049(0.048)	(−0.101)
	Huayuan	0.427(0.431)	0.146(0.143)	(−0.081)

tion of each parameter follows the normal distribution with mean μ and standard deviation σ. These moments are estimated from the samples and given in Table 4. Since the model parameters have some physical meaning and should vary within an acceptable region (Guo, 1995), in this simulation study, the value of *SMAX* is constrained to vary between 100 and 200 mm, and the other four parameters are constrained in the range between zero and one. The Monte Carlo procedure is used to study uncertainties of parameter estimates and runoff. The parameter sets are generated randomly from a truncated normal distribution.

To check the feasibility of the above procedure, the statistics of a synthesized parameter sample of size 1000 were computed by the unbiased method of moments. The results are listed in Table 4 in parentheses. Table 4 shows that the estimated sample mean and standard deviation are very close to the underlying distribution statistics, and that the sample skewness (*Cs*) is close to zero, confirming the hypothesis of normality. This proves that the procedure proposed above is reliable. The model efficiency (R^2) and relative error (*RE*) were also calculated for each iteration. The relationship of R^2 *vs* RE is shown in Fig. 1. It can be seen from the figure that the points at the Huayuan basin are much more scattered than those at the Nantang basin. This implies that the uncertainty of the model parameters at Huayuan basin is much larger than that of Nantang basin.

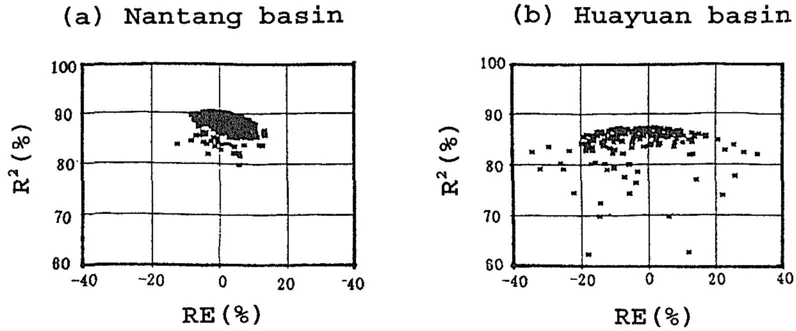

Fig. 1 Model performance expressed in terms of *RE* and R^2 for the 1000 generated parameter sets for the Nantang and Huayuan basins.

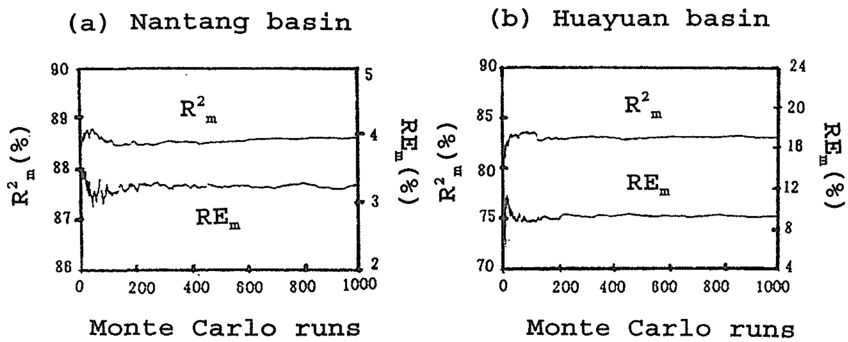

Fig. 2 The $R^2{}_m$ and RE_m *vs* the number of realizations for the Nantang and Huayuan basins.

To obtain statistically reliable results, a large number of Monte Carlo runs must be made before convergence of the model output uncertainty is obtained. For each basin, 1000 simulations were run over the complete data periods. For each run, the R^2 and *RE* were compiled. To permit statistical treatment of the results, it is important that the number of simulations be large enough. The mean R^2 ($R^2{}_m$) and mean *RE* (RE_m) were plotted after each realization (Fig. 2). The convergence of $R^2{}_m$ and RE_m shows that the chosen number of realizations is sufficient.

UNCERTAINTY ANALYSIS OF CLIMATE CHANGE IMPACT ASSESSMENT

Since the runoff is calculated by the chosen water balance model, model parameter uncertainty will result in runoff uncertainty. Therefore analysis of the impact of climate change on hydrology and water resources is also uncertain.

In each iteration, average monthly mean discharge *QM* and maximum monthly discharge *QMAX* were calculated. The proposed Monte Carlo experiment was run 1000 times and the corresponding runoff series of QM_i and $QMAX_i$, where $i = 1, \ldots, 1000$, were formed. The statistical characteristics of runoff series are listed in Table 5.

Table 5 Statistics and confidence bounds of simulated runoff.

Basin	Runoff	μ_Q	σ_Q	Cs	$Q_{50\%}$	$\delta Q_{5\%}$	$\delta Q_{95\%}$
Nantang	*QM*	73.47	0.036	0.005	73.58	−5.85%	5.68%
	QMAX	305.36	0.062	−0.134	307.75	−10.07%	10.53%
Huayuan	*QM*	30.15	3.664	−0.216	30.36	−19.50%	19.14%
	QMAX	317.68	57.20	−0.327	326.26	−26.51%	32.35%

Although the model parameter is assumed to be normally distributed, the runoff series QM_i and $QMAX_i$ are biased, see Table 5. This may be due to the nonlinear structure of model and the uncertainty of the parameters.

The classical method of frequency analysis depends on the assumption of the parent distribution and has some disadvantages and limitations (Guo, 1991). Therefore, a nonparametric method is used to analyse runoff series. In the nonparametric approach, the EV1 kernel is chosen and the smoothing factor of the kernel function is estimated by a modified maximum likelihood criterion. The probability density function f(Q) and distribution function $P(Q)$ of QM_i and $QMAX_i$ series were estimated by a nonparametric procedure (Guo, 1993, 1995). Only the f(Q) and $P(Q)$ of QM_i and $QMAX_i$ at Nantang basin were plotted on Fig. 3. To assess the variation of runoff series of QM_i and $QMAX_i$, the runoff values $Q_{5\%}$, $Q_{50\%}$ and $Q_{95\%}$ which correspond to $P = 5\%$, $P = 50\%$ and $P = 95\%$ were obtained. If the median value $Q_{50\%}$ is chosen as a standard, then the runoff change rate $\delta Q_{5\%}$ and $\delta Q_{95\%}$ may be calculated as $\delta Q_{5\%} = (Q_{5\%} - Q_{50\%})/Q_{50\%}$ and $\delta Q_{95\%} = (Q_{95\%} - Q_{50\%})/Q_{50\%}$. Therefore, the lower and upper bounds of QM and

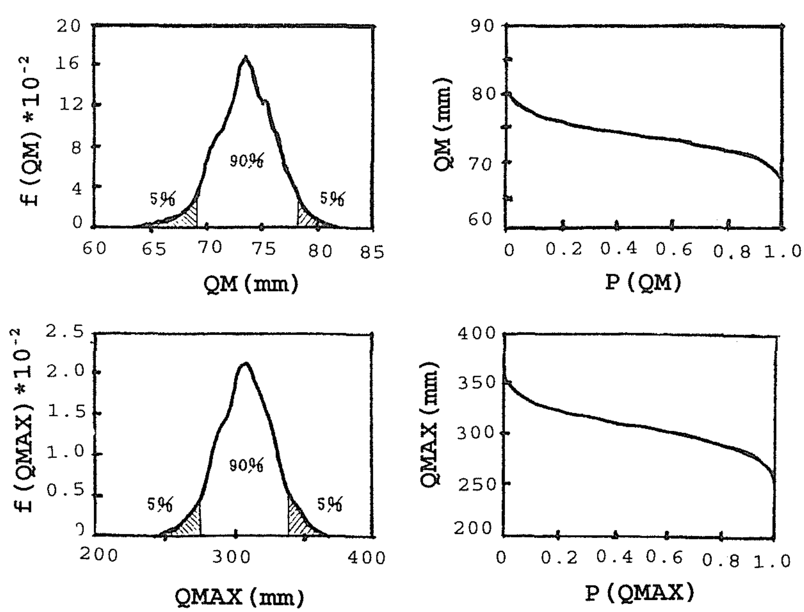

Fig. 3 The probability density function f(Q) and distribution function P(Q) of QM_i and $QMAX_i$ series at Nantang basin.

QMAX at Nantang basin are from −5.86% to 5.68% and from −10.07% to 10.53%. At Huayuan basin the corresponding figures are from −19.5% to 19.14% and from −26.51% to 32.35%, see Table 5. The uncertainties of runoff from the Huayuan basin are much larger than from the Nantang basin.

Based on GCMs output, the most likely climatic scenario in the southern China is a temperature increase of 1 °C and rainfall increase by 10% when the concentration of CO_2 in atmosphere is doubled. If we consider the uncertainty of GCM output and assume the standard deviation of temperature and rainfall variation are 0.25 and 5% respectively, then the variation of temperature δT and rainfall δP should be in the range 0.5-1.5 °C and 5-15% (10% confidence interval assuming δT and δP are normally distributed). The runoff change rate of *QM* and *QMAX* series under different significance levels and climatic scenarios were calculated and listed in Table 6. For a temperature increase of 1 °C and a rainfall increase of 10%, *QM* and *QMAX* in the Nantang basin will increase by 14.71% and 27.63%, respectively.

Table 6 Runoff change rate under different climatic scenarios(%).

Basin	Runoff series	Baseline (mm)	δT=0.5			δT=1.0		
			δP=5%	δP=10%	δP=15%	δP=5%	δP=10%	δP=15%
Nantang	*QM*	71.31	7.54	16.58	25.63	5.73	14.71	23.76
	QMAX	305.47	21.30	28.20	35.14	20.73	27.63	34.55
Huayuan	*QM*	30.29	6.27	20.20	34.27	2.08	15.81	29.81
	QMAX	319.43	7.83	15.91	22.76	5.13	15.06	21.93

SUMMARY AND CONCLUSIONS

The impact of possible climate change on hydrological balance and water resource systems in China has been studied extensively in recent years (Guo, 1995). A procedure for the uncertainty analysis of climate change impact assessment was proposed and analysed in this paper. The main conclusions are summarized as follows:

(a) The proposed monthly water balance model is capable of producing both the magnitude and timing of monthly runoff and soil moisture conditions.

(b) Runoff is more sensitive to precipitation variation than to temperature increase. In the case of the Nantang basin, if δT is fixed at 1 °C and precipitation increases from 5% to 15%, then the *QM* increases by 5.73% to 23.76%. If δP is fixed at 10% and temperature increases from 0.5 °C to 1 °C, then the *QM* is reduced from 16.58% to 14.71%.

(c) The uncertainties of model parameters and runoff are large if the basin runoff coefficient α is small, e.g. the $\delta Q_{95\%}$ value of *QMAX* equals 10.53% at the Nantang basin where α = 0.521 and 32.35% at the Huayuan basin where α = 0.327. The smaller the runoff coefficient is, the larger are the uncertainties.

(d) If we consider the most likely climate scenario (temperature increase of 1 °C and rainfall increase of 10%) and the model uncertainty with 5% significance level (upper bound), then the *QMAX* is expected to increase 38.16% in the Nantang basin and 47.41% in the Huayuan basin, which will seriously affect flood protection work and water resources systems in the south of China.

Acknowledgements The author wishes to record his thanks to Dr R. K. Kachroo for smoothing the manuscript.

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