Inverse Modeling of Water Resources Risk and Vulnerability Under Changing Climatic Conditions

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1. Abstract

It is expected that the global climate change will have serious impacts on both the average water availability and the frequency of extremes. In hydrology, traditional climate change impact studies have been conducted using a top-down approach. Problems related to this approach include a high degree of uncertainty associated with GCM outputs as well as an increased uncertainty due to the downscaling techniques. This work presents an inverse approach to the modeling of water resources risk and vulnerability to changing climatic conditions. The proposed approach first identifies critical hydrologic exposures that may lead to local failures of existing water resources systems. A hydrologic model is used to simulate the main hydrologic exposures, such as floods and droughts. In the next step, the local critical events are transformed into corresponding meteorological conditions. A generic weather generator is developed to simulate the critical meteorological conditions under present and future climatic scenarios. The critical meteorological situations frequently leading to local failures, represented by a certain set of weather generator parameters, are then related to large scale weather sequences. In such way, the risk failure for a given weather scenario can be directly assessed from the weather generator parameters. In the final stage, the frequency of critical weather situations is investigated under future climatic conditions. Since the analysis of GCM outputs is one of the last steps in the proposed methodology, the approach allows easy updating, when new and improved GCM outputs become available. The outcomes of this research will be applied to the Seyhan River Basin study area.

2. Introduction

The potential impacts of climate change on water availability and the regime of hydrologic extremes, have received considerable attention from hydrologists during the last several years. A broad review of the possible impacts of climate change is provided in the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC, 2001).

The past decade produced a number of studies focused on the assessment of climate change impacts. Kite (1993) studied the impact of a $2\times CO_2$ scenario on a mountainous basin in BC, Canada. Zwiers et al. (1998) examined the return period of extreme precipitation under a $2\times CO_2$ scenario. Southam et al. (1999) explored the sensitivity of the Grand River basin (ON) to different future climate scenarios. Rouse (2000) studied the impacts of climate change on the Mackenzie River basin in northern Canada. Payne et al. (2003) simulated snowpack and streamflow in the Columbia River basin (BC).

Climate change impact studies are traditionally conducted using a top-down approach. In the top-down approach, outputs from Global Circulation Models (GCM) are statistically or dynamically downscaled to the river basin scale. The local climatic signal is then used as an input into a hydrologic model to assess the direct consequences in the basin. Problems related to this approach arise from the incompatibility between GCM and river basin temporal and spatial scales. Serious effort is required to validate GCM outputs and the downscaling techniques. As a consequence, many river basin authorities are sceptical regarding the possible adverse impacts of climate change.

This report summarizes an attempt to improve the understanding of the processes leading to hydrologic hazards by developing an inverse approach to the modeling of water resources risk and vulnerability to changing climatic conditions. The approach first identifies critical hydrologic exposures at the local, river basin scale, and then by means of a weather generator links the exposures with GCM outputs.

3. Inverse Modeling of Climate Change Impacts

The inverse approach to the modeling of the potential impacts of climate change on water resources is aimed at assessing the vulnerability of river basins to climate forcing from a bottom-up perspective. The approach consists of the following five steps:

1. In the initial stage, critical hydrologic exposures that may lead to local failures of water resources systems in a given river basin are identified and analyzed together with existing guidelines and management practices. The vulnerable components of the river basin are identified together with the risk exposure. The water resources risk is assessed from three different viewpoints: risk and reliability (how often the system fails), resiliency (how quickly the system returns to a satisfactory state once a failure occurred) and vulnerability (how significant the likely consequences of a failure may be).
2. In the next step, the critical hydrologic exposures (such as floods and droughts) are transformed into corresponding critical meteorological conditions (e.g. extreme precipitation events, sudden warming). A hydrologic model is used to establish the inverse link between hydrologic and meteorological events. Reservoir operations, flood-plain management and other human interventions on runoff, are also included in the model.
3. A generic weather generator, based on the K-nearest neighbour (K-NN) algorithm (Yates et al., 2003, Sharif and Burn, 2004) is used to simulate the critical meteorological conditions under present and future climatic scenarios. The weather generator produces synthetic weather data that are stochastically similar to the observed data. Since the focus is on extreme events, the generator reflects not only the mean conditions, but also the statistical properties of extremes.
4. The critical meteorological events frequently leading to local failures, represented by a certain set of weather generator parameters can be related to the corresponding large scale weather sequences. In such way, the risk failure for a given weather scenario can be directly assessed from the weather generator parameters.
5. In the final stage, the frequency of large-scale weather sequences causing specific water resources risks can be identified from various GCM outputs for future climatic conditions. Since the analysis of GCM outputs is the last step in the proposed methodology, the approach will allow easy updating, when new and improved GCM outputs become available.

The presented approach can be used for the development of hazard risk management strategies under future climatic conditions for any water resources system. In contrast to the traditional top-down approach, the inverse model is targeted at specific, existing water resources problems, and thus has a direct link with the end-user.

4. Illustrative Case Study

In order to illustrate the methodology, the first three steps outlined above are currently tested in the Upper Thames River Basin (UTRB) in Ontario, Canada. The UTRB has a drainage area of 3450 km^2 and outlets to the Lower Thames Valley segment of the Thames River, which is a tributary to Lake St. Clair. The population of the UTRB is 460,000. The main urban centre in the UTRB is the city of London, which was designated a growth centre in the province of Ontario. Other urbanizing centres in the UTRB have also expanded boundaries significantly in recent years. Much of the present urban growth is centered either along the Thames River corridors or expanding along tributaries, vulnerable both from a flood perspective but also increasingly from an ecologic perspective. Urban growth is still contrasted by a significant agricultural land base consisting of increasing intensive farming pressures.

Floods and droughts represent the main

hydrologic hazards in the UTRB. Snowmelt is the major flood-producing factor in the UTRB, generating flood events most frequently in March. High flood events, with magnitudes sometimes exceeding the magnitudes of snowmelt-induced floods, are generated by intensive summer storms. The frontal rainfall type of floods is frequent at the end of autumn. Also, severe flooding situations generated by a combination of frontal rainfall with intensive snowmelt occurred in the past. Periods of low flows usually occur during the summer, and the risk of droughts is highest in the months of July and August.

For the purposes of hydrologic modeling, the UTRB was divided into 34 subbasins by means of the US Army Corps of Engineers's (US-ACE) HEC-GeoHMS software (US-ACE, 2000a). The delineated subbasins, together with 17 streamflow and 21 precipitation gauges available in the study area are depicted in *Figure 1*.

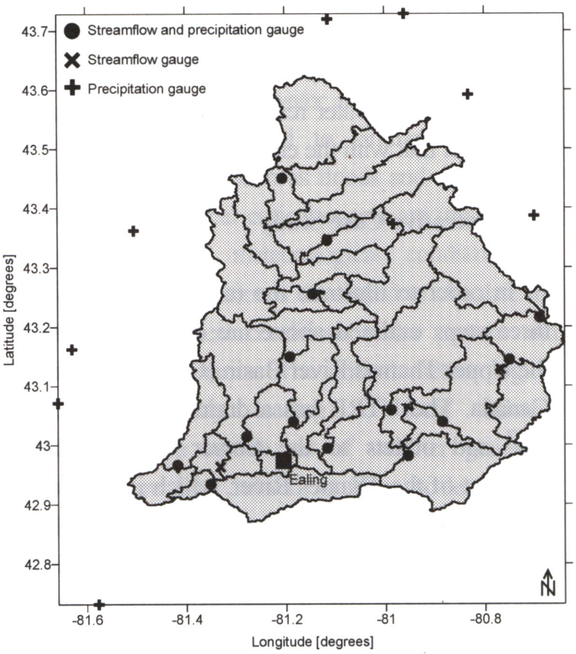

Fig. 1 The division of the Upper Thames River basin into 34 subbasins and the locations of streamflow and precipitation gauges used in the study.

The 34 subbasins represent fine spatial resolution for semi-distributed hydrologic modeling of the UTRB. The HEC-HMS hydrologic model (US-ACE, 2001) is used for modeling both individual (single) rainfall events as well as long, continuous sequences of precipitation data. In the single-event mode, the initial and constant method is applied for runoff-volume computing, the Clark UH method for direct runoff modeling, the modified-puls method for channel routing, and the recession method for baseflow modeling. In the continuous mode, detailed accounting of the movement and storage of water is modeled by the five-layer soil-moisture accounting (SMA) method (US-ACE, 2000b). A detailed description of the selected individual rainfall-runoff events and the data used for continuous hydrologic modeling is provided in Cunderlik and Simonovic (2004). *Figure 2* shows an example of the performance of the model in reproducing the July 2000 flood at the Thames River near Ealing (gauge location depicted in Figure 1 by the black square).

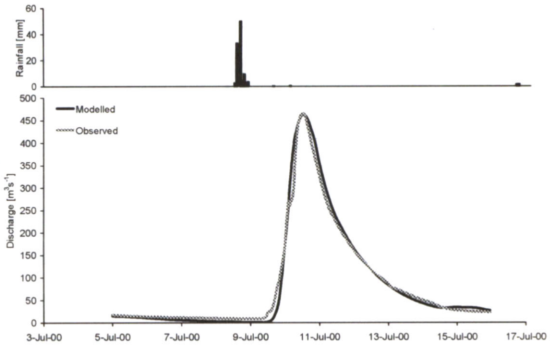

Fig. 2 The July 2000 flood at the Thames River near Ealing (ID 02GD001).

Several hazardous situations and critical failures, such as residential and infrastructure flooding or significant property damages, have been identified in various locations of the UTRB. By means of the hydrologic model, the local hazardous situations are linked with the parameters of corresponding critical hydrologic events. *Table 1* lists examples of hazardous situations in the city of London as a function of two parameters of the critical flood events: peak discharge and stage.

The SCS hypothetical storm is one of many methods that can be used to identify rainfall events that could generate such hydrologic exposures. The SCS method contains rainfall intensities arranged to maximize the peak runoff for a given storm depth and a given geographic region (SCS, 1986).

Table 1 Critical hydrologic events, corresponding rainfall depths and resulting hazardous situations for the Thames River near Ealing (ID 02GD001)

Peak Q(1) (m^3s^{-1})	Peak S(2) (mm)	Rainfall(3) (mm)	Resulting hazardous situation
280	3,530	59	City commences patrolling river banks
520	4,200	95	Adelaide street flooding begins
600	4,370	105	Property flooding along Kennon Place and Southwest of Wellington St Bridge
790	4,683	130	Top of dyke along Nelson St
900	4,850	143	Property damages along Thames St South of York
1100	5,100	167	Thames St/York St intersection inundated

(1)peak discharge, (2)peak stage, (3)based on the SCS Type II hypothetical storm

Different combinations of the SCS storm depths and basin initial conditions (such as antecedent soil moisture or reservoir storage) have been defined and modeled in the UTRB. *Table 1* shows the results for the storm depths corresponding to the most extreme scenario in which the study basin is considered in the saturated state.

Once the critical rainfall depths corresponding to a given basin state were identified, their frequency of occurrence can be determined under present and future climatic conditions from the sequences of synthetic data simulated by the weather generator. In this study the CGCM output for greenhouse gas with aerosol simulation scenario was used to obtain a long term annual increase in the mean temperature for the 2010-2039 period. Strategic resampling was then carried out to derive the driving data set for the K-NN weather generator. The increased precipitation scenario was based on a 100 mm increase. The results showed that the increased temperature scenario produced increased return periods of the critical rainfall depths. The scenario of increased precipitation on the other hand led to smaller return periods of the critical storms compared to the present conditions.

5. Conclusions and Recommendations for the Future Work

This report introduced an inverse, bottom-up approach to the modeling of water resources risk and vulnerability to changing climatic conditions. In contrast to traditional climate change impact studies, the inverse approach first identifies critical hydrologic exposures at the local, river basin scale, and then, links them with GCM outputs through the parameters of a weather generator. Since the analysis of GCM outputs is one of the last steps in the proposed methodology, the approach allows easy updating, when new and improved GCM outputs become available.

Future work will involve application of the presented methodology to the Seyhan River Basin.

(a) In the initial stage, critical hydrologic exposures that may lead to local failures of water resources systems in Seyhan River Basin will be identified and analyzed together with existing guidelines and management practices.

(b) The critical hydrologic exposures (such as floods and droughts) will be transformed into corresponding critical meteorological conditions in the basin. Continuous hydrologic model will be developed to assist in this task. One possible choice is the continuous simulation version of the HEC-HMS model that includes seven components that describe the main hydro-climatic processes in the river basin. The meteorological component will be the first computational element by means of which precipitation input will be spatially (interpolation, extrapolation) and temporally (interpolation) distributed over the basin. The spatio-temporal precipitation distribution can be accomplished by the inverse-distance interpolation method (IDM). The IDM algorithm computes hyetographs for all selected locations in the basin. A quadrant system is drawn centered on a given location. A weight for the closest rainfall gage, that does not have missing data, is computed in each quadrant as the inverse, squared distance between the gage and the location. The closest rainfall gage in each quadrant is determined separately for each time step. When the closest gage has missing data, then the next closest gage in a quadrant is automatically used (USACE, 2000a).

Precipitation distribution over previous and impervious surfaces of the basin will be further used in the model. Precipitation from the pervious surface is subject to losses (interception, infiltration and evapotranspiration) to be modeled by the precipitation loss component. The 5-layer soil-moisture accounting (SMA) model can be used to estimate and subtract the losses from precipitation. The SMA model is based on the Precipitation-Runoff Modeling System, and can be used for simulating long sequences of wet and dry weather periods. There are four different types of storage in the SMA model: canopy-interception storage, surface-depression storage, soil-profile storage, and groundwater storage (the model can include either one or two groundwater layers). The movement of water into, out of, and between the storage layers is administered by precipitation, evapotranspiration, infiltration (movement of water from surface storage to soil storage), percolation (from soil storage to groundwater storage 1), deep percolation (from groundwater storage 1 to groundwater storage 2), surface runoff (output), and groundwater flow (output). For computational details of the SMA model see USACE (2000a). Precipitation from the impervious surface runs off with no losses, and contributes to direct runoff.

The output from the precipitation loss component contributes to direct runoff and to groundwater flow in aquifers. The Clark unit hydrograph can be easily used for modeling direct runoff. In the Clark method, overland flow translation is based on a synthetic time–area histogram and the time of concentration, *Tc*. Runoff attenuation is modeled with a linear reservoir. The groundwater flow is transformed into baseflow by a linear reservoir baseflow model. In this model, outflows from SMA groundwater layers will be routed by a system of baseflow linear reservoirs.

Both overland flow and baseflow enter the river channel. The translation and attenuation of water flow in the river channel will be simulated by the modified Puls method. This method can simulate backwater effects (e.g. caused by dams), can take into account floodplain storage, and can be applied to a broad range of channel slopes. The modified Puls method is based on a finite difference approximation of the continuity equation, coupled with an empirical representation of the momentum equation. The effect of hydraulic facilities (reservoirs, detention basins) and natural depressions (lakes, ponds, wetlands) can be reproduced by the reservoir component of the model. The model solves recursively one-dimensional approximation of the continuity equation.

(c) A generic weather generator (WG), based on the K-nearest neighbour (K-NN) algorithm (Yates et al., 2003, Sharif and Burn, 2004) will be used to simulate the critical meteorological conditions under present and future climatic scenarios. The weather generator produces synthetic weather data that are stochastically similar to the observed data. Since the focus is on extreme events, the generator reflects not only the mean conditions, but also the statistical properties of extremes. WG allows for the creation of an ensemble of climate scenarios that will be used in integrated assessment.

The K-nn nonparametric WG uses the Mahalanobis distance metric, which does not require explicit weighting and standardization of variables. The Mahalanobis distance weights the variables with their covariance, which attributes less weight to strongly correlated variables. The algorithm samples the daily weather at the stations within a region simultaneously, and thus preserves the correlation structure between the stations and among variables. The bootstrap resampling retains non-Gaussian features in the probability density functions of the model variables. The approach can also simulate inter-annual and intra-annual climate variability. Technical details of the approach are described in Yates et al. (2003) and are not repeated here.

(d) The critical meteorological events frequently leading to local failures, represented by a certain set of weather generator parameters will be related to the corresponding large scale weather sequences. In such way, the risk failure for a given weather scenario can be directly assessed from the weather generator parameters.

(e) In the final stage, the frequency of large-scale weather sequences causing specific water resources risks will be identified from various GCM outputs for future climatic conditions. The approach will allow easy updating, when new and improved GCM outputs become available.

The final outcomes of the study will be translated into new hazard mitigation guidelines and vulnerability reduction strategies for improved flood and drought prevention and robust water management under changing climatic conditions in the Seyhan River basin.

6. References

Cunderlik, J.M. and S.P. Simonovic, (2004) Selection of calibration and verification data for the HEC-HMS hydrologic model. CFCAS Project report II, UWO, London, ON, January 2004.

IPCC (Intergovernmental Panel on Climate Change) (2001) Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of the Working Group II to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

Kite, G.W., (1997) Simulating Columbia River flows with data from regional-scale climate models, *Water Resources Research*, 33(6): 1275-1285.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer and D.P. Lettenmaier, (2003) Mitigating the effects of climate change on the water resources of the Columbia River basin, *Climatic Change*, 62(1): 233-256.

Rouse, W., (2000) MAGS 1 scientific achievements – an overview. In: The Mackenzie Basin Climate and Water Resources: Understanding the past and predicting the future, Proceeding of the 6th scientific workshop, Saskatoon, SK: 412-418.

SCS, (1986) Technical Release 55: Urban hydrology for small watersheds, Department of Agriculture, Washington, DC.

Sharif, M. and D.H. Burn, (2004) Development and Application of a K-NN Weather Generating Model. Project Report III, UW, Waterloo, ON, March 2004.

Southam, C.F., B.N. Mills, R.J. Moulton and D.W. Brown, (1999) The potential impact of climate change in Ontario's Grand River basin: water supply and demand issues, *Canadian Water Resources Journal*, 24(4): 307-330.

US-ACE, (2000a) Hydrologic Modeling System HEC-HMS. Technical Reference Manual, US Army Corps of Engineers, Hydrologic Engineering Center.

US-ACE, (2000b) Geospatial Hydrologic Modeling Extension HEC-GeoHMS. User's Manual, Version 1.0. US Army Corps of Engineers, Hydrologic Engineering Center.

US-ACE, (2001) Hydrologic Modeling System HEC-HMS. User's Manual, Version 2.1. US Army Corps of Engineers, Hydrologic Engineering Center.

Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek, (2003) A technique for generating regional climate scenarios using a nearest-neighbour algorithm, *Water Resources Research*, 39(7): 1199, doi:10.1029/2002WR001769, 2003.

Zwiers, F.W. and V.V. Kharin, (1998) Changes in the extremes of the climate simulated by CCC GCM2 under CO2 doubling, *Journal of Climate*, 11(9): 2200-2222.