行政院國家科學委員會專題研究計畫成果報告

區間數模糊線性規劃模式在氣候變遷對水資源影響評估之應用

Application of Interval Number Fuzzy Linear Programming to Climate Change Impact Assessment of Water Resources

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一、中文摘要

自然界具有不確定性，如河川流量之隨機特性；而人類認知行為亦具有不定性，如對用水需求量之滿意度。由於人為大量排放溫室氣體，導致大氣溫室效應加強，而可能造成全球性之氣候變遷。氣候改變會直接衝擊水資源，不僅會影響供水量，也會影響需求量。台灣地區豐枯水期水資源可利用量差異大，因此必須藉由蓄水措施調節，氣候變遷影響供需水量，亦將影響蓄水容量之需求。蓄水容量可藉由線性規劃進行優化分析，然傳統的線性規劃方法中，係數與限制式右端常數皆設為確定數，且其解唯一。然而，許多問題皆具有不確定性，用確定數難以表示其特性。因此，有些研究利用序率線性規劃模式來探討此問題，然而序率方法需要有足夠的資料去檢定機率分佈函數，故在資料不足時較不可行。本研究提出區間數模糊線性規劃方法，以區間數描述自然不確定性，模糊集合描述人類對水資源需求量滿意度之不確定性，提供另一分析不確定性之途徑，並將其應用於氣候變遷對水資源影響評估之研究中。本研究之目的在建立氣候變遷對蓄水容量需求之影響評估方法，除了模擬評估氣候變遷對供需水量之影響外，提出區間數模糊線性規劃方法以推求未來在氣候變遷下最佳蓄水容量需求。

關鍵詞：區間數、灰數、模糊集合、線性規劃、氣候變遷、全球暖化

Abstract

Uncertainty exists in both nature and human knowledge. For example, stream flow has random characters, and human satisfaction of water demand could not be described by an exact value. Greenhouse effects are enhanced due to increasing greenhouse gases emitted by human activities, which may result in global climate change. Climate change will directly affect water resources, not only water supply but also water demand. The quantity of available water resources in wet and dry seasons is very different in Taiwan, so storage is required to store water for later uses. Climate change will influence water supply and demand, and thus may affect storage requirement. Storage capacity can be determined by linear programming. Traditional linear programming model contains only constant right hand side and coefficients of the objective function and constraints. However, there exists uncertainty in water resources systems. Uncertainty cannot be incorporated in the optimization framework if deterministic parameters are used. Some studies use stochastic process to describe uncertainty. However, the stochastic method requires more information for analysis, which is impossible sometimes. Interval number fuzzy linear programming model (INFLP) is proposed in this study and is applied to climate change impact assessment. The INFLP uses interval number to describe natural variability and fuzzy set to describe uncertainty of human decisions. The purpose of this study is to develop a procedure to evaluate the impacts of climate change on water resources. The procedure includes simulation and optimization models. The simulation model is to evaluate the climate change impacts on stream flows and demand. On the other hand, the INFLP is applied to find optimal storage capacity can be determined for future climate change condition.

Keywords: Interval Number, Grey Number, Fuzzy Set, Climate Change, Global Warming

INTRODUCTION

Increasing in atmospheric greenhouse gases could cause global warming, which in turn may result in changes of precipitation and temperature. Climate change will directly influence water resources. Many researches have evaluated the impacts of climate change on water resources. The most widely reported effects on streamflows are due to the changes of precipitation and temperature. Many studies (Glieck, 1987; Gan, 1990; bulton et al., 1992; Tung and Haith, 1995) have found that global warming would change monthly streamflow. Beside of analyzing the climate change impacts on streamflow, this study also evaluated reservoir capacity requirement for future climate condition.

There is uncertainty in climate change impact study. Most impact studies are based on climate change scenarios downscaling from the predictions of General Circulation Models (GCMs). Because the processes of global warming and their interactions are complex, there are lots of uncertainties in the predictions of GCMs and the downscaling processes.

Linear programming (LP) model is simple and often applied to water resources planning, but the method itself is lack of ability to deal with uncertainty. A LP model is to maximize or minimize a linear function with linear constraints. Normally, mean values of coefficients are used for a model. Thus it is not easy to reflect uncertainty of a system. Linear programming with chance constrained (Loucks et al., 1981) can help to deal with uncertainty. However, it needs more efforts to analyze the probability distribution of concerned information.

Fuzzy linear programming (FLP) model (Negoita, 1976) has been applied to many research areas. A fuzzy linear programming could maximize the minimum value of membership functions among objective and constraints.

Interval analysis is a methodology to deal with interval programming (IP), which contains interval numbers in coefficients and right hand side (Moore, 1966). Interval number linear programming (INLP) is the branch of the interval analysis theory. Interval number linear programming (INLP) was introduced to solve the best and worst optimal solutions (Tong, 1994) from combinations of interval coefficients and right hand sides.

Tong (1994) incorporated interval number and fuzzy number into a LP model. Similar approach was used in this study, which is called interval number fuzzy linear programming (INFLP) model in this study. The INFLP model was proposed to deal with uncertainty for climate change impact assessments. Reservoir capacity requirements were determined to meet water demands, flood mitigation, and conservation purposes. Thus, reservoir capacity includes flood mitigation space, active storage, and minimum storage or dead storage. Active storage depends on water demand and inflows. Inflows and water demands under climate change can be evaluated, but with uncertainty. It is difficult to find probability distributions to describe the uncertainty.

Instead, interval numbers can be applied to indicate possible range of inflows and demands. On the other hand, the satisfaction of water supply is based on human decision, which can be described by fuzzy set. Thus, membership function can be applied to describe the satisfaction level of water supply. The purpose of this study is to propose framework which includes the INFLP model and simulations for water resources planning under climate change condition. Besides, for simulating inflows, the WatBal model is modified in this study.

METHODOLOGY

A simulation/optimization framework was proposed for evaluating the impacts of climate change on the requirements of reservoir capacity that depends on water demands and inflows. Inflow was simulated by the modified WatBal model and water demands were projected for different climatic conditions. Then, reservoir capacity was minimized by a INFLP model.

Fuzzy sets and interval numbers were used to describe the satisfaction of services and the uncertainty of water demands and inflows. The satisfaction of water supply may tolerant little deficits, which was described by a fuzzy set. On the other hand, different GCMs predict different change of temperature and precipitation and thus result in different future inflows. Interval numbers were used to describe the range of inflow. Then, a INFLP model was formulated for reservoir capacity planning under climate change.

The flowchart of this study is shown in Figure 1. Climate change scenarios are derived from GCMs' outputs, and then future weather data were generated based the scenarios and historical weather data. Future weather data were used to project future water demand, and input the modified WatBal model to simulate inflows for climate change conditions. After modified water demands and simulated inflows, a INFLP model was formulated to determine the optimal reservoir capacity.

Simulation Model

The WatBal model (Yate, 1996), developed based on the study of Kaczmarek (1993), was modified in this study.

The WatBal model is revised to simulation monthly streamflow. The WatBal is a conceptual and lumped water balance model (Kaczmarek, 1993). The inputs are precipitation and temperature, and outputs include evapotarnspiration and streamflow. Surface runoff, subsurface runoff and evapotranspiration are presented as the functions of relative soil water storage. There is a differential equation to describe water balance of soil moisture as follows:

$$S_{\max}\frac{dz}{dt} = P_{eff}(1-\beta) - R_s - R_{ss} - R_b - Ev$$

where S_{max} is maximum catchment water holding capacity; z is relative storage; βP_{eff} is direct runoff (R_d), R_s is the surface runoff; R_{ss} is subsurface runoff; R_b is base flow; Ev is evapotranspiration. Total runoff, for each time step, is the sum of four components:

$$R_t = R_d + R_s + R_{ss} + R_b$$

Surface runoff is defined as follow:

$$R_s = Max\left[0, z^{\varepsilon}(P_{eff} - R_b)\right]$$

Above equation allows the surface runoff term to approach zero as relative storage becomes very small, and ε is a constant parameter. R_{SS} in the term of non-linear reservoir system can be defined as follow:

$$R_{ss} = \alpha\, z^{\gamma}$$

The control equation for evapotranspiration can be defined as follows:

$$Ev = PET\ z$$

Evapotranspiration is a function of potential evapotranspiration (PET) and the relative catchment soil water storage state. A number of expressions have been given to describe evapotranspiration as a function of soil moisture state (Kaczmarek, 1991).

According to the equation of surface runoff above, the total runoff will excess precipitation when z approaches to 1. The surface runoff should be a function of P_{eff}, R_b, and Rd, and thus the equation was modified as:

$$R_s = Max\left[0, z^{\varepsilon}(P_{eff} - R_b - R_d)\right]$$

INFLP Model

Different GCMs normally predict different changes of precipitation and temperature, and thus result in different future inflows and water demands. Interval number can be used to describe the ranges. With the uncertain information, an INFLP model can be formulated as the M1 model. The $[v_b^*, v_w^*]$ was determined by the INLP model. The deficits of 5%-20% were considered in this study to setup dl_t, dy_t, and df_t.

$$Max\ \lambda$$

$$S.T.$$

$$\lambda \le 1 - \frac{V}{[v_w^*, v_b^*]}$$

$$V \ge S_t$$

$$S_{13} = S_1$$

$$\lambda \le 1 - \frac{l_t - S_t}{dl_t}$$

$$\lambda \le 1 - \frac{[y_t^+, y_t^-] - (S_t - S_{t+1} + [q_t^+, q_t^-])}{dy_t}$$

$$\lambda \le 1 - \frac{f_t - (V - S_t)}{df_t}$$

$$t = 1, \ldots, 12$$

$$All\ Variable \ge 0\ \&\ 0 \leqq \lambda \leqq 1$$

EXPERIMENT DESIGN

The water supply system of the Tsengwen reservoir, located on the Tsengwen creek, Taiwan, is chosen as the study site. The predictions of the CCCM, GFDL, and GISS models were used to derived climate change scenarios.

The Site Description

The watershed area of the Tsengwen reservoir is 489 km^2. The average inflow is 37.3 cms. The 85% of annual streamflows are distributed in the typhoon season, May through October. Historical records show that the maximum 3-day inflow is 574.2 million cubic meters. With the 75-year recurrent time, the design flood of the project is the 3-day maximum probable flood, 437 million cubic meters. The reservoir is designed for agricultural, industrial, and domestic water users. The annual demands of agriculture, industry, and domestics are about 900 million cubic meters (86%), 27 million cubic meters (3%), and 120 million cubic meters (11%), respectively.

Climate Change Scenario

The climate change impacts on water resources were evaluated using three climate change scenarios based on the predictions of CCCM, GFDL, and GISS. Mean monthly temperature and precipitation under $1xCO_2$ and $2xCO_2$ are taken from the nearest grid points in GCMs. The change of temperature of a watershed in future is assumed to be the same as the difference of temperatures between $2xCO_2$ and $1xCO_2$ conditions. The change of precipitation is considered as a fraction of precipitation in $2xCO_2$ climate condition to that in $1xCO_2$ climate condition. The relationships are given as follows.

$$\mu'_{mT} = \mu_{mT} + (\mu_{mT,2\times CO_2} - \mu_{mT,1\times CO_2})$$

$$\mu'_{mP} = \mu_{mP} \bullet (\mu_{mP,2\times CO_2} / \mu_{mP,1\times CO_2})$$

where μ_{mT} and μ'_{mT} are current and future mean monthly temperature (°C), $\mu_{mT,1\times CO2}$ and $\mu_{mT,2\times CO2}$ are simulated mean monthly temperatures (°C) under $1\times CO_2$ and $2\times CO_2$ climate conditions; μ_{mP} and μ'_{mP} are current and future mean monthly precipitation (cm), $\mu_{mP,1\times CO2}$ and $\mu_{mP,2\times CO2}$ are simulated mean monthly precipitation (cm) under $1\times CO_2$ and $2\times CO_2$ climate conditions. The predictions of the GCMs (1995 version) are downloaded from US Country Studies Program in the NCAR ftp site (ftp://ncardata.ucar.edu/pub).

Design of Agricultural Water Demand

Two scenarios of future agricultural water demands were considered in this study. One is assumed the same as current demand without climate change effects; the other is modified by the change of potential evapotransipration in climate change. The change of rainfall may affect agriculture water demand, but it is not considered in the study.

SIMULATION RESULTS

The validations of the modified Watbal model, the results of simulated streamflows and optimized reservoir capacity for climate change are described here.

Validation of the Modified WatBal model

The Table 1 shows the calibrated parameters of the modified WatBal model. Further validation study indicates the model providing reasonable predictions. The correlation coefficient is about 0.93, and error is under 1%. The simulated and recorded monthly streamflows are shown in Figure 2.

Impacts on Streamflows

Streamflows were simulated for different climate change scenarios. The results are given in Table 2. It is noted that streamflow tends to increase about 11~28% in the wet period (May to October). Figure 3 shows the maximum and minimum streamflows among three climate change scenarios for each month.

Impacts on Agricultural Water Demand

Using Hamon's equation (1961), the potential evapotranspiration (PET) were estimated for both current and future climates. The future to current agricultural water demands are assumed the same as the ratio of future PET to current PET. The results show in Figure 4, which the PET is changed about 10~30%.

Impacts on Reservoir Capacity

The interval values of v* were determined as [919, 974]. The results are listed in Table 4. There is no feasible solution with 5-15% allowable deficits.

CONCLUSIONS

Uncertainty may significantly influence decisions. Climate change impact study inherits uncertainty from GCMs' predictions, which may bring difficulty to decision makers for finding adaptation strategies. This research provides a framework to assess reservoir capacity under climate change, which includes simulation and optimization models.

Simulation models were used to simulate the impacts of climate change on streamflows and agricultural water demands. Streamflow was simulated by the modified WatBal model, while agricultural water demand was adjusted according to the changes of potential evapotranspiration.

Different GCMs normally predict different climate changes, and thus have different impacts on streamflows and water demands. Interval numbers were used in this study to describe the range of streamflows and water demands under climate change conditions. Besides, the satisfaction of water supply was described by fuzzy relationships. Both interval number and fuzzy relationship were incorporated into a LP model to form an INFLP model. The optimization model was then applied to determine the minimum required reservoir capacity.

Climate change may influence flood magnitude, which could also have effects on reservoir capacity requirement. On the other hand, crop growing periods could become shorter due to higher temperature. Changes of growing periods may further result in different distribution and quantity of agricultural water demand. These two factors were not considered in this study, but require further examined.

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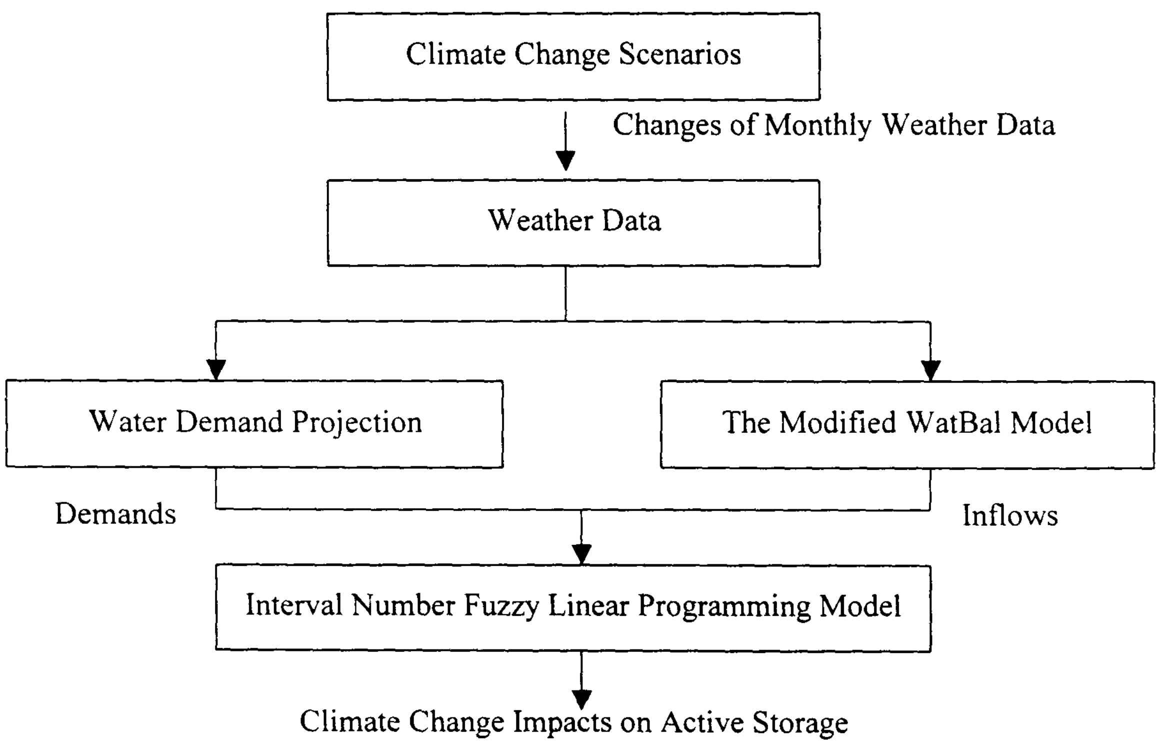

Figure 1 the Flow Chart of this study

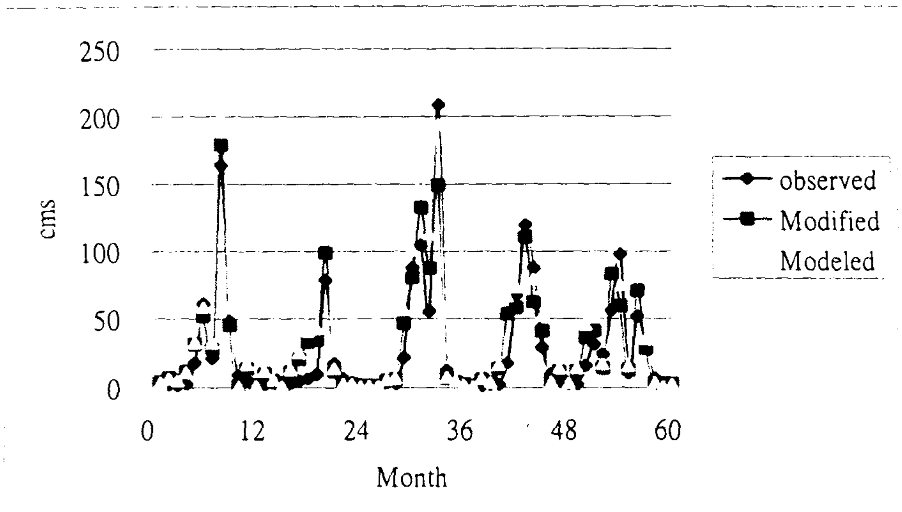

Figure 2 The observed and simulated mean monthly flows of the Tsengwen Reservoir watershed.

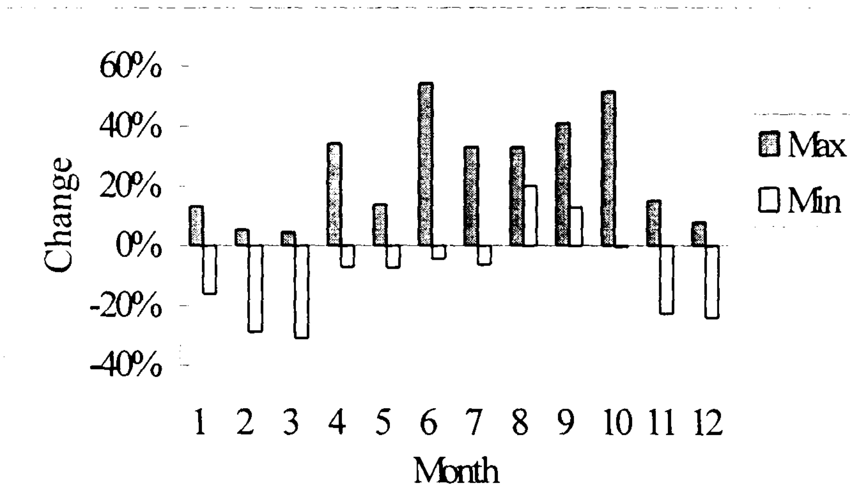

Figure 3 The changes of streamflow under climate change

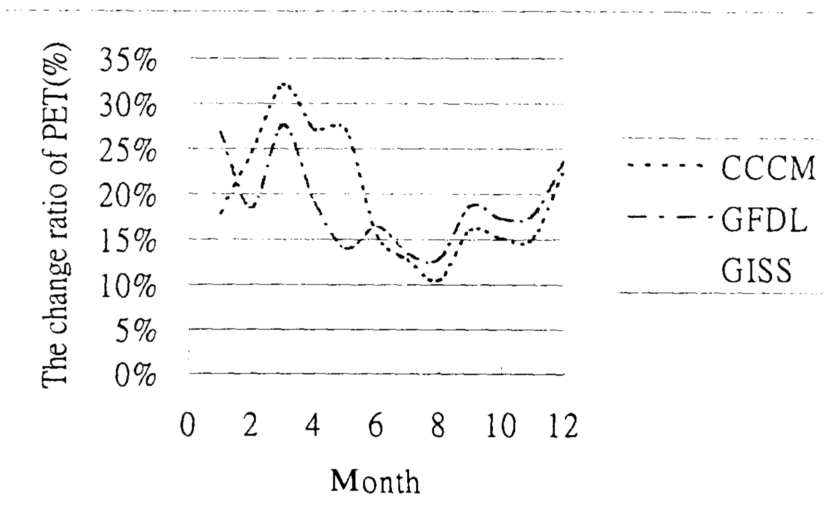

Figure 4 The changes of PET under climate change

Table 1 Parameters of calibration in WatBal

Smax	ξ	α	β	γ
427.5mm	0.525	1.0	0.0	2

Table 2 Streamflow simulated under climate change Unit:cms

Month	1	2	3	4	5	6	7	8	9	10	11	12
Observed	4.8	7.7	10.7	12.6	55.9	78.2	77.7	101.7	43.1	9.7	4.8	2.6
CCCM	4.1	8.1	7.4	14.0	63.6	109.2	78.2	122.0	60.8	9.9	4.3	2.0
GFDL	5.1	7.6	11.0	11.7	60.8	74.9	72.8	135.1	48.7	14.7	3.7	2.8
GISS	5.5	5.5	11.2	16.9	51.9	120.6	103.3	127.7	57.1	9.7	5.5	2.5

Table 3 Optimal reservoir capacity unit: $10^6 m^3$

Fuzzy Deficits		0%	5%	10%	15%	20%
MaxFlow	Min_PET	973	942	915	891	869
MinFlow	Max_PET	*****	*****	*****	*****	871

*****: no feasible solution