Using A System Dynamic Simulation Model to Forecast Long-Term Urban Water Demand

Huien Niu
Department of Town and Country Planning
University of Newcastle upon Tyne
Newcastle, NE1 7RU
UK

Allan A Gillard
Department of Town and Country Planning
University of Newcastle upon Tyne
Newcastle, NE1 7RU
UK

Abstract

Forecasting long-term water demand is essential in water resources planning and management. A common problem existing in long-term forecasting is that many uncertainties are involved due to the various assumptions which can be used. Thus, it is highly desirable to give the assumptions explicitly in a long-term forecasting. By using system dynamic simulation, scenarios can be easily produced based on different assumptions, or by issuing different valued to the parameters and initial variables. And the assumptions can be stated explicitly and organized systematically by presenting the alternatives in tables. The frequency distribution of the forecast results, which are obtained from different scenarios, can be derived. A range of forecasts, rather than a single forecast, can be produced. This can possibly supply an overall picture of a forecast.

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INTRODUCTION

Forecasting long-term urban water demand is essential in water resources planning and management. In particular, facing the threat of urban water scarcity, strategies and policies are required, and these need to be based on reliable water demand forecasts. The benefits of better long-term water demand forecasting arise from the avoidance of under- or over-investment and efficient supply.

Forecasting, according to Armstrong (1978, p6), is concerned with determining what the future will look like, and planning is concerned with what the future should look like. A plan must identify what the world will look like without intervention, and also what the world will be like if different assumptions are made about the future, and what the world will look like if planning intervention occurs. These are the jobs of forecasting. Forecasting will be present, explicitly or implicitly, whenever planning, of virtually any kind, is undertaken (Gardiner and Herrington, 1986, p7-16). There are both objective and subjective components involved in forecasting, since a forecast is a conditional statement about the future. The objective component consists of explaining past levels and patterns, while the subjective component is the application of the resultant knowledge to the future (Boland, 1985; Jones, et al., 1984; Prasifka, 1988). A problem existing in long-term forecasting is that many uncertainties are involved due to the various assumptions which can be used. Thus, it is highly desirable to present the assumptions explicitly in forecasting.

The methods that have been developed in the literature of water demand forecasting are usually based on some static causal relationships between water demand and one or more explanatory variables, such as those single and multiple coefficient methods, which are derived from analysing historical data. Using these methods, the variable of time is implicitly included, the assumptions behind the forecast are not stated explicitly, and the uncertainties of the forecast are greatly obscured by the static relationships employed.

In the light of the above discussion, the purpose of this paper is to describe an approach that introduces system dynamic simulation into long-term water demand forecasting. The system dynamic model that has been developed in this research is generally based on the analysis of the Chinese urban water system (see Figure 1). The factors considered in the model are the significant factors which are derived from analysing Chinese urban water use.

OVERVIEW OF THE MODEL

(1) A distinction made between two kinds of factors and a simple adjustment to the single coefficient method

Among the factors that have been found to influence water use, it is possible to distinguish those that determine the demand for water and those that affect the intensity of water use. For each water use sector, a factor which is the indicator of the size or scale of the sector is chosen to be the factor affecting the demand for water. Other factors are related to the per unit water use, such as per capita, per employee, per unit productive value, per unit area, etc., or recognized as those affecting the intensity of water use. Although it is made subjectively, the distinction creates a possibility to consider more variables in water demand forecasting by using the simple form of single coefficient methods, and it makes some relationships easier to understand.

A general mathematical model of the single coefficient methods may be summarized in the following simple form:

$$Q = cX + e \qquad (1)$$

in which Q is the quantity of water used or demand in a time period; c is the water per unit use (per capita, per connection, or other unit); X is the explanatory variable; and e is the error term, or residual, with an expected value of zero.

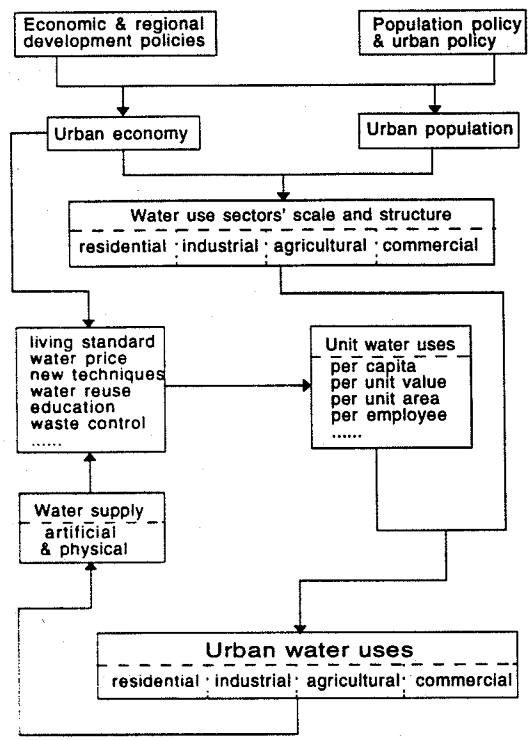

Figure 1 Urban Water Use System

According to the distinction, the single coefficient methods that are commonly used in long-term water demand forecasting can be adjusted to be:

$$Q = U * X + e \qquad (2)$$

in which $U = f(X_1, X_2, X_3, \dots)$ (3)

where Q is the quantity of water demanded; U is the per unit water use (per capita, unit value product, etc.); X is the determinant variable affecting the demand for water; and $X_1, X_2, X_3, \dots$ are the variables affecting water use intensity, or affecting the per unit water use.

(2) A conceptual procedure and the acquisition of dynamic equations

To answer the question of "how much water will be demanded by a water user in a future time?" normally involves answering four interrelated questions, or a four-step procedure:

(1) How much water is currently, or recently, used?

(2) Will the water use in a future time be different from the current or recent use?

(3) If the answer to the second question is "yes", then, what are the motivations (factors) which cause the difference or change? and

(4) How will the factors (motivations) influence water use?

Assuming the current water use is Q_0, and water use in a future time is Q_t, according to the answer to the questions, the relationship between them can be expressed by the following simple equation:

$$Q_t = Q_0 + DQ \qquad (4)$$

in which DQ is the change term of water use from current time to the time t.

Similarly, future per unit water use U_t can be expressed as:

$$U_t = U_0 + DU \qquad (5)$$

Based on Equation 3, and according to a general answer to the third question, which is derived from causal analysis, the change term DU can be expressed as:

$$DU = f(DX_1, DX_2, DX_3, \dots) \qquad (6)$$

All the independent variables and the dependent variable in Equation 6 can be regarded as changing with time. Thus, a differential equation about the time variable Dt is:

$$DU/Dt = f(DX_1/Dt, DX_2/Dt, DX_3/Dt, \dots) \qquad (7)$$

Let $R_u = DU/Dt$

Then $U_t = U_0 + Dt * R_u$ (8)

And $U_t = U_0 + Dt * f(DX_1/Dt, DX_2/Dt, DX_3/Dt, \dots)$ (9)

R_u might be called the change rate of per unit water use. It may be represented by the differential form of dU/dt.

(3) The system dynamic simulation model

Based on the causal relationships that are derived from analysing Chinese urban water use, a system dynamic simulation model was built by using the Professional DYNAMO. It is composed of four subroutines: residential, industrial, agricultural, and commercial, which are identical with the four water use sectors disaggregated in the analysis. The relationships between water use and the factors considered in each sector are described in Figure 2 to Figure 5 by using dynamic flow diagrams.

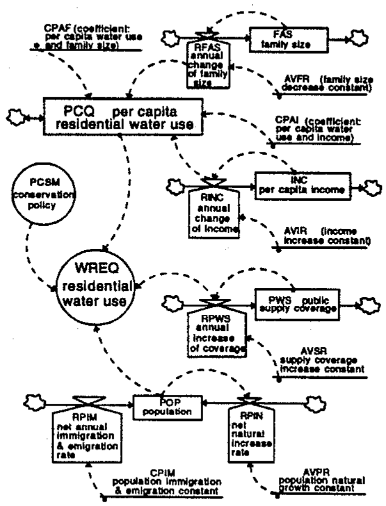

Figure 2 Flow Diagram of residential water use

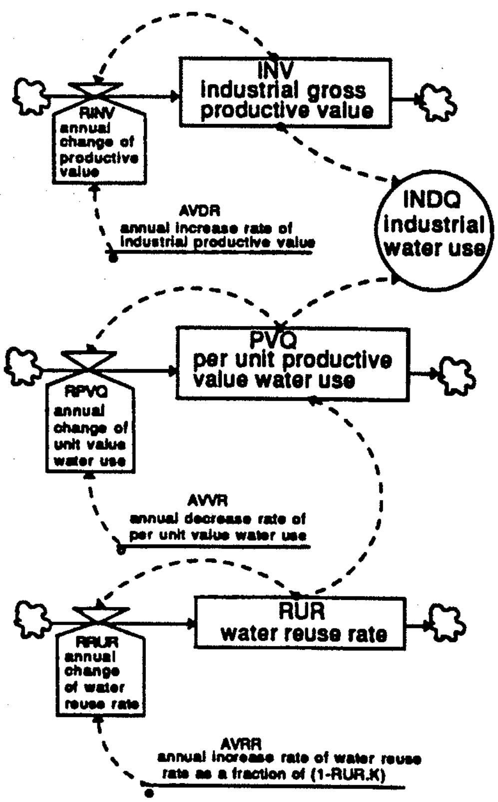

Figure 3 Flow Diagram of industrial water use

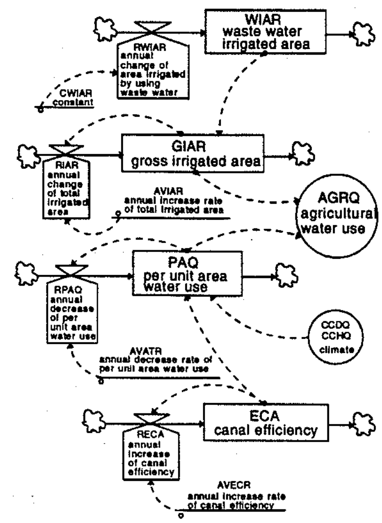

Figure 4 Flow Diagram of agricultural water use

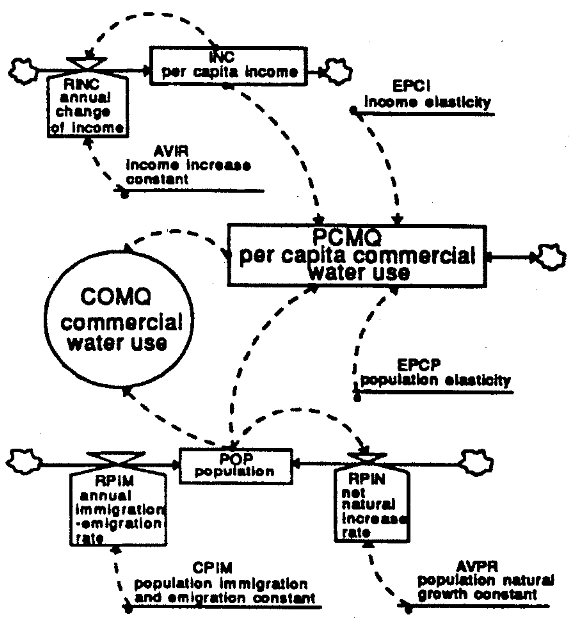

Figure 5 Flow Diagram of commercial water use

By issuing different values to the parameters and initial variables in the model, alternatives forecasts, or scenarios, can be easily obtained, since simulation is a formal way of systematically asking and answering the question, 'what happens if this is done?' (Meta Systems Inc., 1975). Adopting the procedure described by Whitford (1972) to deal with scenarios or uncertainties, a frequency distribution of the forecast results, which are obtained from different scenarios, can be derived. Thus, a range of forecasts, rather than a single forecast, is produced.

The model is a very general one, in terms of its model structure, variables concerned, undecided parameters, etc. When it is applied in practice, there are certain flexibilities in determining the structure, the variables of concern, and the values attributed to the parameters. Several strategies are suggested for dealing with these issues.

Firstly, within each subroutine or sector, further divisions are possible. The level of further disaggregation is greatly dependant on data availability and the inner-structure or constitution of the water use sector, which is much related to the special case being studied. The method of forecasting used to deal with further divided sub-sectors is similar to that used for the aggregate sector, although different values might be given to the initial variables and parameters.

Secondly, in terms of the variables concerned, for any particular city which is restricted by data availability or any other special local situation, different proxies of the factor that influences the demand for water may be adopted. For example, numbers of industrial employees may be used instead of the industrial productive value in the industrial subroutine. On the other hand, more exogenous variables that influence the intensity of water use, or per unit water use, may be combined into the model, if relationships between water use and these variables are proven to exist. However, different proxies of one factor are not allowed to appear simultaneously in the forecasting model, in order to avoid double counting.

When extra or more variables are considered to be combined into the simulation model, there are generally two approaches which can be followed. One is to relate them with the per unit water use by finding out the coefficients or elasticities; another is to treat them as adjustment factors by estimating their effects on water use without introducing them into the model explicitly.

Thirdly, the adoption of values, or alternative values, for parameters, coefficients, and elasticities basically follows the principle of 'respecting the special case being studied', although literature and engineering analyses are very useful for determining some of these. It is believed that better understanding of the local situation about water use will result in more reliable forecasts.

And finally, for determining and modifying the coefficients and elasticities, or evaluating the performance of the model, historical validation can be used. Using the model that has been built, not only water demand in the future but water demand in the past can be projected. By comparing the projections with the historical records, it can be assessed whether or not the model produces accurate forecasts. Except for the coefficients and elasticities that are uncertain, all the other parameters are determined in forecasting past water demand. If the model does not produce accurate forecasts, through the procedure of trial and error, the values attributed to the coefficients and elasticities may be adjusted until acceptable forecasts are produced. If the model produces accurate forecasts, it may be used as a proof of its reliability. However, when using historical records to prove the reliability of a forecast model, the question of whether or not the pattern or relationship which existed in the past will continue in a long-term future arises. The important aspect of system dynamics model-building is to try to ensure that the model structure properly reflects the mechanisms for change.

ASSESSMENT OF THE MODEL

After applying it to forecasting urban water demand by the city of Lanzhou in China, the performance of the model is evaluated from three aspects: (1) the variation in the forecast results; (2) sensitivity analysis; and (3) comparisons between the forecasted water uses and the historical records which are available from 1987 to 1990.

(1) The variation in the forecast results

In general, the statistical analysis on the results of the alternative forecasts reveals that the Standard error and the Range of forecasts increase with the time horizon. This confirms the principle that the further the forecast, the more the uncertainty is. The variance of the forecasted results is influenced by the alternative values adopted for the parameters. When quite different alternatives are adopted for the parameters, running the simulation model will produce very changeable results. Therefore, care should be paid to determining the parameters. When there is much uncertainty about the alternatives chosen, it is necessary to give much thought to making an assumption. An upper limit should also be considered for the forecast time horizon, in order to get reliable results by using this model. In this study, thirty years ahead from the base year is the suggested answer.

(2) Sensitivity analysis

For each sector and for each variable, parameter, or constant, different values were input to test the sensitivity of the model by reference to the variation of the model outputs. This enables both a testing of model structure and a better understanding of model performance. The sensitivity analysis shows that the model is more sensitive to changes in some parameters than in others. This explains that different parameters play different roles in influencing the variation of water demand forecasts. The percentage of change in future water demand caused by a certain change in a parameter, is generally determined by the time horizon, the initial value estimated for the parameter, and the significance of the factor that the parameter represented or related.

In the residential subroutine, the parameters in relation to the factors of population and income are those which are most responsible for the change in residential water use. In the industrial subroutine, the parameters related to the 'other industrial group', which excludes thermo-electrical, chemical and petroleum industries, play the more important roles. This is because water demand by this industrial group in Lanzhou urban area is projected to increase much faster than the other three kinds of industry. Future agricultural water demand is more sensitive to the change in technological improvements in irrigation and water transfer methods. Commercial water demand is almost equally sensitive to the changes in its parameters related to population and income.

(3) Comparisons between the forecasts and historical records

Restricted by data availability, only a short-term comparison was possible between the forecasts and historical records for three water use sectors. The values of forecast chosen to compare were those that have the minimum difference compared to the mean of all the scenarios made for each water use sector. The number of scenarios made in the case study are 108 for the residential sector, 64 for the industrial sector, 36 for the agricultural sector, and 24 for the commercial sector.

Table 1 indicates that model performance for the period 1987-1990 produces a close 'forecast' from the residential sector, but performs less well for the industrial and commercial sectors. Detailed analyses of these performances suggest that short-term factors have disturbed behaviour of these sectors.

Table 1 Comparisons between Forecasted and Actual Water Use

Years		1987	1988	1989	1990
Residential Water Use					
Actual	(10^4 m^3)	4789	5251	5393	5612
Forecasted	(10^4 m^3)	4971	5143	5317	5494
Forecast error	(%)	3.8	-2.1	-1.4	-2.1
Industrial Water Use					
Actual	(10^4 m^3)	23863	26147	23408	22197
Forecasted	(10^4 m^3)	23405	24070	24710	25370
Forecast error	(%)	-1.9	-7.9	5.6	14.2
Commercial Water Use					
Actual	(10^4 m^3)	1179	1319	1398	1538
Forecasted	(10^4 m^3)	996	1105	1219	1338
Forecast error	(%)	-15.5	-16.2	-12.8	-13.0

CONCLUSION

In summary, the system dynamic simulation model has the characteristics of requiring assumptions to be explicit, it requires a dynamic structure based on causal relationships, then allows the consideration of alternative scenarios. Combined with using the procedure introduced by Whitford (1972), an overall picture of a forecast would be possibly presented by running the model. From the perspective of the model structure and the relationships employed, it can be concluded that the model can produce reliable forecasts. With better estimation of parameters and estimation to model structure, then it will produce accurate forecasts as well.

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