Application of analytical hierarchy process to water resources policy and management in Beijing, China

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Abstract

The Analytical Hierarchy Process (AHP), which is able to provide solutions to problems involved in determining the priorities of various policies, can also be successfully used to approach water policy and management. With regard to the serious water shortage problem in Beijing, China, a 4-level AHP structure is constructed for helping decision making with a main objective and eight sub-objectives. Among the various water policies, 24 policies are examined, and a set of eight constraints is considered as criteria. An expert system is formed to support the judgments through a 4-round AHP questionnaire for different hierarchies in order to diminish the effect of subjective bias. Computations are processed through a modified AHP programme using the characteristic root method. The results provide both qualitative and quantitative information to decision makers on the policies, as well as on their priorities from the point of view of regional water planning and development. The AHP model gives not only the relative importance of each factor for each level, but also the composite weights in relation to the main objective.

Introduction

The application of the Analytical Hierarchy Process (AHP) has been involved in many fields, i.e. energy planning (Nezhad, 1982), resource allocation (Karagalein, 1982), alternative waste treatment policies (Saaty, 1982), talent promotion (Ramanujam, 1983), human migration (Harker, 1986), health insurance (Odynocki, 1982), and business (Wind, 1980). The reason for this is due to the characteristics of the method itself, summarized as follows.

(a) Simple formulation. AHP reflects the human way of thinking, which makes it possible to be applied to the real world, and it provides a medium for "conversations" between planners, decision makers and analysts or researchers.

(b) Systematicity. It decomposes a large system into a framework within which one can consider a diversity of interrelated factors of engineering, environmental, economic, political and social nature, and analyze their complex mutual interactions and impacts. In spite of the explicitness involved in the basic idea, it contains a profound philosophic theory.
Practicality. It can be applied to nearly any aspect related to evaluation of alternatives and the planning-making process.

Since water resources planning is a complex dynamic process, and belongs to large-scale systems problems, the application of an analytical hierarchy process becomes necessary.

Background Description in the Case Study of Beijing

Water shortages in Beijing have become more and more serious in recent years due to the dramatic increase of water demand from industries, agriculture and domestic use. On the one hand, the industrialization and urbanization upstream of the basin tend to cause shortages of regional surface water supply, and the overexploitation of aquifers causes a decrease in the groundwater level. On the other hand, water pollution due to the discharge of waste into water bodies indirectly diminishes the amount of water available. Accordingly, a lot of research is being carried out by experts on various countermeasures. There are two advantages for using AHP:

(a) The formation of various policies are available, such as exploitation (construction of new reservoirs), water conveyance from the southern regions, extension of municipal sewage treatment plants for reuse of treated water, city economy planning, etc.

(b) The corresponding quantitative and qualitative results and data of different policies from a series of sub-studies such as the Beijing Water-Economy Input/Output Model (Xie et al., 1987) and the Beijing Water Resources System Dynamics Model formed a base for the next step study.

Hence, the objective deals with how to answer the following questions:

1. What is the prerequisite for solving the water shortage crisis? How should the objectives of city planning be determined?

2. How should various policies be evaluated, and how should priorities of the variety of practices be determined?

3. How should the restrictive factors involved in the implementation of policies and their effects be considered?

The above questions involve hydrological engineering, environment, economy, administrative reform and social effects.

AHP as a Powerful Tool in Decision Analysis

A brief introduction to methodology. AHP was first developed in the early 1970's by Thomas L. Saaty and has played an important role in modern decision-making fields (Saaty, 1980, 1982b; Forman, 1985). When the AHP logic hierarchical structure is formulated, one should first yield the judgment matrices based on pairwise comparison of all elements in each hierarchy with respect to the higher hierarchy according to certain criteria of comparison within certain scales. The scales are given in Table 1 (Saaty, 1983):
Table 1. Scale of relative importance.

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance of one over another</td>
<td>One is slightly in favor over another</td>
</tr>
<tr>
<td>5</td>
<td>Essential or strong</td>
<td>One is strongly in favor over another</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
<td>One is strongly favored and its dominance is demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Absolute importance</td>
<td>The evidence favoring one over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>2, 4</td>
<td>Intermediate values</td>
<td>When compromise is needed between the two adjacent judgments</td>
</tr>
<tr>
<td>6, 8</td>
<td>Reciprocals of above numbers</td>
<td>If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared to i</td>
</tr>
</tbody>
</table>

The basic idea of AHP is that the factors in a complex system are grouped on different logic levels, forming a chain, or hierarchy, whereby the lower-level elements can be compared in pairwise matrices with respect to the higher level, and so on, so that finally the composite priorities of all levels are achieved.

There are still imperfections both in theory and in practice:

(a) The knowledge background and personal preference of the analysts and the degree of understanding of the systems can have a strong effect on the elements in the judgment matrix and hence the results of priority. Expert advisory-network, as the support system to the AHP model, can overcome the above defect to a large extent, but may cause inconsistency of judgment matrices.

(b) The objectivity of consistency criteria needs to be further investigated.

Closing the Gap Between Theory and Practice

This paper is based on the results of "Research of Water Policy and Management in Beijing and the Surrounding Areas," which was sponsored by the National Science and Technology Committee. After the results from sub-project reports were submitted to the general workshop, a variety of countermeasures or policies of solving the crisis of the water shortage
were established. For decision analysis of the priorities of alternatives considering both quantitative and qualitative information, AHP was adopted as an auxiliary analytical tool.

To apply AHP, it was necessary to establish an expert advisory system, otherwise the judgment matrix could be influenced by subjective opinions of modelers. There were 63 experts from more than 30 sectors that responded to our 4-round questionnaire, including city government and administrative organizations, decision departments, economic and planning companies, municipal and public services, environmental protection and water supply bureaus, industries and research institutes, etc. The principles for expert advisory group formation are: (i) they should be experts from related departments of interest, and (ii) knowledge background and age group, which can affect the effectiveness of the judgments, should also be taken into consideration.

Two ways are followed while compiling the results from the questionnaire to determine the elements in the judgment matrix:

(a) In most cases, the minority submits to the majority. In mathematics, the mean or mode is used.

(b) If the opinions are very different, then the backgrounds of the questionnaire respondents are taken into consideration before making a choice.

The Application of AHP to Beijing Water Resources Policy Making

General framework. The working process consists of several parts, as shown in Fig. 1. The structure of AHP was carefully chosen and modified so as to avoid the model bias due to the facts that (a) the pairwise comparison becomes difficult when the factors in the same hierarchy are unappropriately chosen, and (b) the evaluation of policies is not comprehensive because of the incomplete consideration of factors. A representation of a 4-level AHP structure is shown in Fig. 2.

Determination of hierarchies and their factors. First level: target (T)

T: solve the water shortage so that the city, as a capital, can have its normal activities in cultural and economic development.

Second level: strategies (or sub-objectives) (S)

S1: guarantee for industrial water use
S2: guarantee for agricultural water use
S3: guarantee for third industrial water use (services, transportation, communication, universities and institutes)
S4: guarantee for domestic water use
S5: guarantee for environment and recreation water use (parks, grasslands, trees, etc.)
S6: guarantee for reservoir regulation in case of extra use
S7: guarantee for water recharge in order to maintain the groundwater balance
S8: develop the regional economy and expand reproduction
Third level: constraints (or criteria) (C)

C1: negative environmental effect
C2: restricted economic development
C3: defect in institutional management and legal systems
C4: shortage in water supply
C5: water pollution
C6: restriction of funding
C7: social and traditional impediment
C8: technical feasibility

Fig. 1. AHP model formulation process.
Fig. 2. Hierarchical representation of water policy formulation.

Fourth level: policies (or countermeasures) (P)

- P1: construct Zhangfang reservoir
- P2: deep groundwater exploitation
- P3: water conveyance from Yangzhi river
- P4: water conveyance from Yellow river
- P5: water conveyance from Luan river
- P6: increase water reuse rate in industries by recycling and multi-use and decrease water consumption per capital
- P7: develop water-saving facilities for irrigation using advanced techniques like drop and sprinkling irrigation
- P8: install water-saving facilities for public services and domestic sanitation
- P9: reinforce user’s management through installing water meters and diminish water loss by propagation and education
- P10: decrease agricultural water supply
- P11: build municipal sewage treatment plants
- P12: build reuse systems for residential areas
P13: increase use of treated water for irrigation
P14: establish a centralized water-management and planning institution and reform the present systems
P15: enforce legal systems for water exploitation and utilization
P16: regulate water-price policy and quota
P17: conjunctive use of surface and groundwater
P18: afforest upstream areas and prevent erosion
P19: city industrial structure regulation
P20: change crop structure and land use pattern
P21: increase grain import from other regions and decrease irrigation areas
P22: restrict the scale of industrial increment
P23: control of population growth
P24: control of rural enterprises water use

Information From Expert Support System

The first-round table provides a flexible form, allowing those interviewed to give their opinions and criticism on suggested policies, to add or modify them, and to list the possible effective factors for policy implementation. The information will help determine C and P level factors. Levels for the main target, T, and strategies of sub-objectives, S, are set up mainly through government planning sectors.

The second-round questionnaire is based on the centralized first-round results, of which 8 constraints and 24 policies are finally chosen (see Fig. 2) dealing with 8 main aspects:

1. water exploitation within the region
2. canal water from outer regions
3. water conservation, making full use of available water
4. reutilization of urban discharged water by reuse of the treated water
5. administrative and institutional system reforms
6. conjunctive use of surface and groundwater
7. regulation of economic water use structure
8. planning of social and economic development scales.

The interviewees are asked to answer two kinds of questions:

(a) Give for each policy the possible value of its implementation in the near future (1-5 years), middle-run (5-10 years), and long-run (10-20 years).

(b) For each constraint Cα of level C, give the pairwise comparison of Policies P1 and Pj in level P. For instance:

C1 (environmental impact): answer "Which of the two policies, P1 and P2, has less environmental effect?" The same for P1 and P3, etc. (the scoring follows the same scales shown in Table 1).

C4 (water supply): answer "Which of the two policies, P1 and P2 can provide more water?" The same for P1 and P3, etc.
C6 (funds): answer "Which of the two policies, P1 and P2 cost less?" The same for P1 and P3, etc.

The third-round questionnaire is concerned with T-S and S-C levels (see Fig. 2). To answer:

(a) Which of the strategies, S1 and Sj (i, j = 1,2, . . ., 8), is more important for the main target?

(b) Which of the constraints, C1 and C2 is more critical to strategy S1? The same for C1 and C3, C2 and C3, etc.

The fourth-round questionnaire is a feedback to experts of computational results on priorities for the purpose of modifying the AHP model.

Results Analysis

The computation is performed on a modified AHP program using BASIC. The eigenroot method is used and provides a fast convergence. The results for levels T-S-C are summarized in Table 2, where the first row is the priority of strategy conditional to target T. Each column stands for the priority value of constraints C in coping with strategy Sj. The last column is the composite weight vector of constraint level C to T.

Table 2. Priorities of level T-S-C.

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>CW</th>
</tr>
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<tbody>
<tr>
<td>S1</td>
<td>.108</td>
<td>.101</td>
<td>.121</td>
<td>.312</td>
<td>.099</td>
<td>.074</td>
<td>.094</td>
<td>.092</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>.123</td>
<td>.129</td>
<td>.062</td>
<td>.153</td>
<td>.086</td>
<td>.810</td>
<td>.098</td>
<td>.142</td>
<td>.119</td>
</tr>
<tr>
<td>C2</td>
<td>.106</td>
<td>.109</td>
<td>.297</td>
<td>.070</td>
<td>.052</td>
<td>.147</td>
<td>.038</td>
<td>.000</td>
<td>.100</td>
</tr>
<tr>
<td>C3</td>
<td>.102</td>
<td>.058</td>
<td>.038</td>
<td>.094</td>
<td>.123</td>
<td>.142</td>
<td>.063</td>
<td>.047</td>
<td>.084</td>
</tr>
<tr>
<td>C4</td>
<td>.235</td>
<td>.253</td>
<td>.257</td>
<td>.299</td>
<td>.239</td>
<td>.180</td>
<td>.189</td>
<td>.287</td>
<td>.256</td>
</tr>
<tr>
<td>C5</td>
<td>.146</td>
<td>.167</td>
<td>.108</td>
<td>.161</td>
<td>.171</td>
<td>.093</td>
<td>.157</td>
<td>.142</td>
<td>.147</td>
</tr>
<tr>
<td>C6</td>
<td>.130</td>
<td>.084</td>
<td>.115</td>
<td>.074</td>
<td>.170</td>
<td>.129</td>
<td>.176</td>
<td>.316</td>
<td>.131</td>
</tr>
<tr>
<td>C7</td>
<td>.086</td>
<td>.116</td>
<td>.063</td>
<td>.082</td>
<td>.073</td>
<td>.090</td>
<td>.165</td>
<td>.067</td>
<td>.090</td>
</tr>
<tr>
<td>C8</td>
<td>.073</td>
<td>.085</td>
<td>.060</td>
<td>.066</td>
<td>.087</td>
<td>.130</td>
<td>.115</td>
<td>.000</td>
<td>.073</td>
</tr>
</tbody>
</table>

The results show that:

(a) Under the main target T, "domestic water use" S4 has the highest weight (0.3120), which largely exceeds the alternative ones. This means that Beijing, as a capital city, should take care of domestic water consumption in the future. The second is S3 (0.121), which is connected with S4 by including public services, transportation, etc. S1, S2, S5, S7 and S8 have nearly the same value of 0.09 - 0.10, indicating the same level of importance. In this case, it is difficult to say that one is more important than the other just by a little difference in weights.
(b) Among the eight selected constraints, "water shortage" has the highest priority (0.256), which largely exceeds the other ones. This means that it will be the most urgent factor. The next most crucial constraints are C5, "water pollution," and C6, "lack of funding," with values of 0.147 and 0.131, respectively.

With respect to the main scenario, the overall composite weights are listed in Table 3. The results indicate that:

(a) The highest weight (0.0879) is found for policy P1, i.e. construct Zhangfang reservoir. It is located in the southwest part of Beijing, and can provide enough water for a big oil manufacturing factory, as well as domestic use of the surrounding areas. The second priority (0.0753) is found to characterize policy P2, i.e. groundwater exploitation. These two policies demand that water exploitation within the region should be put into the first place to meet future water demand.

(b) Among the 24 selected water policies, "build municipal wastewater treatment plants for water reutilizing" has a high priority of 0.0684. It will be, apart from seeking new sources, the most urgent and effective way to reduce indirectly water consumption by reuse of treated water.

(c) The next most important policy is P3, i.e. "water conveyance from Yangzhi River" (0.0657). In spite of its high cost and possible environmental effect, it still gets a high priority for the long-run.

(d) "Economizing water use by increased reuse rate in industries" (P6) and "decrease water demand in agriculture through high technique irrigation" (P7) have great potential. This means the reduction in water demand through technological and procedural changes without affecting productivity.

(e) P14, i.e. "establish a centralized water management and planning institution," and reform the present system of "multi-dragon control" to "general dragon control," which
82 X. Mei, R. Rosso, G.L. Huang and G.S. Nie

seemed to be held by many investigators, has only a weight of 0.0366, and it is placed in the 16th order out of 24 policies due to its social and traditional obstruction.

(f) "Regulate the innerstructure and interstructure of industries and agriculture" (limit those sectors that consumer large amounts of water) takes precedence over policies P10, P21, P22 and P24, which restrict the development of industries and agriculture on the whole.

Conclusions

To summarize our experience, the following conclusions can be made.

(a) Since the imperfect definition of factors may cause either difficulty in comparison or omission of information, AHP structure identification and element selection of each hierarchy can hence have a direct effect on the results.

(b) The skill of establishing the questionnaire tables, the way of putting questions, and showing respect to the interviewee do play an important role on the judgments.

(c) A weighted emphasis could be necessarily attached to expert groups according to their specialties when there is inconsistency on the judgments.

Like other systems analysis methods, AHP still has its limits for application. But nevertheless, the research shows that in dealing with the decision-making problems of a multi-hierarchy and multi-variable system, AHP provides a powerful tool through synthesizing various options and finally gives both qualitative and quantitative analyses, and the process itself is in fact a process of understanding the complex system.

References


