SUSTAINABILITY APPRAISAL OF TAIPEI MUNICIPAL WATER SUPPLY SYSTEM

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ABSTRACT

The purpose of this study is to develop a simulation model to evaluate sustainability of water supply systems for Taipei municipal and neighbor areas. The definition of sustainability is addressed first, which indicates that sustainable development requires keeping cumulative impacts not exceeding environmental carrying capacity. The carrying capacity of a water supply system is the quantity of potential water supply which depends on water resources facilities and hydrological conditions. Thus, sustainability of a water supply system needs total water demands less than its potential water supply capacity. Besides, difference between water demand and water supply should be in an acceptable range (such as 10% of water supply). A water supply system dynamics model was developed in Vensim 4.0 for the Danshuei river watershed and applied to evaluate sustainability of Taipei, Banshin, and Shihmen water supply districts. Before appraisal study, historical streamflows were used to verify the model. Validation indicates that the model can provide reasonable simulations. Then, the model was applied to assess sustainability. The results indicate if water loss of distribution system can be improved and Taipei district supply of 5.3×10^5 m^3 d^-1 to Banshin district, three water supply districts are sustainable by year 2025. However, it does not imply no drought event, because carrying capacity of water supply is determined based on the criterion of shortage index = 1.

INTRODUCTION

Rapid economic and social development improves human beings’ livings substantially, but has caused degrading environment and feedback to constrain our future development. Human beings require mining natural resources and discharge wastes to environment to support development. At the initial growth stage, natural environment is able to supply sufficient resources and assimilate limited pollutant discharges. More demands and pollutant discharges are brought by growing human society. Finally, continuous development without careful considerations in environment results in over mining resources and over discharging pollutants to further cause the degradation of environment. Consequently, natural environment gradually looses its ability to support continuous development or even to support survival of human society and ecosystems. Sustainable development has become an important issue in this century since Agenda 21 was proposed. Furthermore, the most important element is not only the concept of sustainable development but also how we can develop quantitative measures to manage environmental sustainability.

Both water quantity and quality are key factors to support development. In the past, economic development led water resources plans. In other words, there were economic plans first and then water resources agency had the obligation to meet their water requirements by building new facilities. However, building new facility becomes more difficult in Taiwan. Most of areas have reached their limits or subject to social and environmental considerations to prohibit large hydraulic installation. Therefore, many economic plans are held due to insufficient water supply. Taking sustainable development as a goal requires having water plans first and then providing information of available water as a constraint for developing economic plans.

Many studies have worked on the study of water resources management [1-4], including those in Taiwan. In order to provide quantitative information for developing sustainable management strategies, evaluation models are necessary. Simonovic [5] mentioned that systematic planning for water resources is complicate and requires computer programming. System
dynamics modeling is a powerful measure to develop a simulation model. Forrester [6] developed a system dynamics model to describe urban dynamics, and Meadows et al. [7] used system dynamics to describe limits to growth. Many researchers have also developed their system dynamics model and applied to water resources systems (e.g., Guo et al. [8]). Thus, system dynamics were applied to build a water supply simulation model to assess sustainability and provide quantitative information in this study.

The definition of sustainability is introduced in the next section. Then, descriptions of study area and development and validation of a water supply system dynamics model are addressed. At last, the model is applied to evaluate sustainability of water supply systems and final remarks are given.

DEFINITION OF SUSTAINABILITY

Sustainable development has become an important issue. Brundtland Commission defines sustainable development as follows.

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” - Brundtland, 1987 [9].

The definition has outlined the spirit of sustainable development. However, it still requires a more quantitative definition to develop sustainable management strategies. Barbier [10] addressed that environmental sustainability should keep the rate of using renewable resources less than renewal rate and discharging pollutants less than assimilation capacity. Since sustainable development requires to meet requirements of both current and future generations and not to degrade environment, it needs to keep cumulative impacts from different generations less than environmental carrying capacity [11]. Cumulative impact is first addressed in the National Environmental Policy Act by Council on Environmental Quality [12] of United States of America. It requests that environmental impact assessment must include potentially cumulative impact.

Cumulative impacts should consider cumulated alteration of environmental integrity from different locations and time periods. As shown in Fig. 1, the “line a” is environmental carrying capacity, “curve b” is a conceptual cumulative impact curve, and “line c” is baseline. The goal of environmental management is to keep “curve b” below “curve a”. Thus, the issues here are how to determine carrying capacity and baseline (lines a and c) and how to avoid “curve b” exceeding “curve a”. The carrying capacity of water quantity is its potential water supply which can be determined based on water resources facility and hydrological conditions. How to determine carrying capacity is discussed more detail in a later section.

TAIPEI MUNICIPAL WATER SUPPLY SYSTEM

Taipei municipal area is located in the Danshuei river watershed. The descriptions of the Danshuei river watershed and water supply systems are addressed in this section. Then, a system dynamics model was developed and verified in a later section.

1. The Danshuei River Watershed

The Danshuei river watershed is located in the northern Taiwan and has three major tributaries, including the Sindian river, the Dahan river, and the Keelung river (Fig. 2). The total length and area of the Danshuei river are 157.8 km and 2726 km$^2$, respectively. Taipei municipal area withdraws water from the Sindian river which has a Feitsui reservoir located in the upstream, while the neighbor water supply districts, Banshin and Shihmen, take water from the Dahan river which has the Shihmen reservoir.

1.1 The Sindian river

The total length and area of the Sindian river is 90 km and 916 km$^2$, respectively. The Beishi river and the Nanshi river are two major tributaries, and are major water resources for Taipei municipal area. The Feitsui reservoir is located in the Beishi river with the active capacity of $4.06 \times 10^8$ m$^3$. Water treatment plants
for Taipei municipal area withdraws flows from the Nanshi river first. If stream flow is insufficient, water will be released from the Feitsui reservoir for supplement. The management principle has been incorporated into the simulated model developed in this study.

1.2 The Dahan River

The total length and area of the Dahan river are 135 km and 1163 km², respectively. Its major tributary is the Sansia river. The Shihmen reservoir is located in the upstream to supply water for Taoyuan irrigation district and Banshin and Shihmen domestic water distribution systems. The capacity of the reservoir is $3.09\times10^8$ m³.

1.3 The Keelung river

The total length and area of the Keelung river are 86 km and 501 km², respectively. There is no reservoir installed in this river. This study focuses on Taipei, Banshin, and Shihmen water supply districts, and thus the Keelung river is not included.

2. Water Supply System

The Taipei municipal and neighbor areas include three major domestic water supply systems, Taipei, Banshin, and Shihmen. Two reservoirs, Feitsui and Shihmen, and several water treatment plants are installed in this area. A conceptual diagram of the water resources system of the Danshuei river is given in Fig. 3.

2.1 Taipei District

Taipei water supply district has three water treatment plants, including Chihtan, Chingtan, and Gongguan. Chihtan Weir delivers water to the Chihtan water treatment plant which has the capacity of $2.70\times10^6$ m³ d⁻¹ (CMD), while Chingtan Weirs store water for Changshin and Gongguan water treatment plant. Total capacity of the three major treatment plants and inlets are $3.82\times10^8$ and $3.80\times10^8$ CMD, respectively (Table 1). These water treatment plants utilize flows from the Nanshi river first, and if it is not sufficient, a request will be sent to the reservoir management bureau to release more stored water. The reservoir management bureau then releases water based on requests and operational rules. The rules are described as follows,

1. Storage is higher than upper threshold: hydro-power generation can be operated 24 h a day and water can be released to downstream to meet requests.
2. Storage is between upper threshold and lower threshold: The first priority of using stored water is to satisfy water demands. Hydro-power generation can be operated 6 h a day.
3. Storage is between lower threshold and extreme lower threshold: The water can only be used for water supply. Hydropower generation plant can only use limited released water.
4. Storage is below extreme lower threshold: Water supply is 30% off, if storage is less than extreme low threshold. Hydropower generation plant can only use limited released water.

Table 1. Water treatment and inlet capacities (unit: $10^6$ CMD)

<table>
<thead>
<tr>
<th>District</th>
<th>Major treatment plant</th>
<th>Capacity</th>
<th>Water sources</th>
<th>Inlet capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taipei</td>
<td>Chihtan</td>
<td>2.70</td>
<td>Chihtan Weir</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>Changshin</td>
<td>0.60</td>
<td>Chingtan Weir</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Gongguan</td>
<td>0.52</td>
<td>Chingtan Weir</td>
<td>1.10</td>
</tr>
<tr>
<td>Banshin</td>
<td>Banshin</td>
<td>1.20</td>
<td>Yuanshan Weir</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sansia Weir</td>
<td>0.50</td>
</tr>
<tr>
<td>Shihmen</td>
<td>Lungtun</td>
<td>0.05</td>
<td>Shihmen Reservoir</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Pinjhen</td>
<td>0.60</td>
<td>Shihmen Reservoir</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Shihmen</td>
<td>0.12</td>
<td>Shihmen Reservoir</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Danan</td>
<td>0.50</td>
<td>Shihmen Reservoir</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yuanshan Weir</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Fig. 3. The water resources system of the Danshuei river watershed.
2.2 Banshin and Shihmen Districts

Major hydraulic facilities in the Dahan river include Shihmen reservoir, Houchih Weir, Yuanshan Weir, Sansia Weir, Shihmen major irrigation ditch, and Taoyuan major irrigation ditch. The intake of Shihmen major ditch is located in the upstream of the Shihmen reservoir, while the intake of Taoyuan major ditch is installed in the Houchih Weir. The Shihmen water supply system has four water treatment plants which withdraw water via Shihmen and Taoyuan ditches. The total capacities of water treatment plants and inlets are $1.27 \times 10^6$ and $1.35 \times 10^6$ CMD, respectively. The Banshin water treatment plant takes water from Sansia Weir first. If it is insufficient, more water is taken from Yuanshan Weir. The capacities of treatment and inlet are $1.20 \times 10^6$ and $2.10 \times 10^6$ CMD. The Banshin district also receives water supply from Taipei district directly.

The Shihmen reservoir is built to store the Dahan river’s flows for both agricultural and domestic water demands. In the Dahan river system, carrying capacity of agricultural water demand is required further examined. The operational rules of the Shih-Men reservoir are described as follows.

1. Storage is more than upper threshold: Hydropower generation as much as possible to reduce storage to the upper threshold.
2. Storage is between upper and lower thresholds: Normal operation. Water supply needs to meet both domestic and agricultural water demands and requirements in the contract with hydropower generation.
3. Storage is between lower and extreme lower threshold: Meet both domestic and agricultural water demands and 80% of requirements in the contract with hydropower generation.
4. Storage is below extreme low threshold: Supply 70% of irrigation water and rigidly manage hydropower generation by only using supplied water for domestic and agricultural demands.

DEVELOPMENT OF SYSTEM DYNAMICS MODEL

1. Systems Dynamics

Forrester [6] applied systems dynamics to simulate urban dynamics which described how a city develops and finally collapses due to exhausting re-
sources. System dynamics have been applied to many research areas. This study also utilizes system dynamics to develop a simulation model to appraise sustainability of water supply systems.

A system consists of many components and functions to describe the relationships between components. System dynamics modeling has three major components, including level, rate, and auxiliary, and uses arrow to link components. Thus, system dynamics modeling can be applied to develop a simulation model more intuitively, especially for water resources systems. For example, a reservoir can be represented by a level component, and its inflows and outflows can be described by the rate components. Besides, operation rules of a reservoir, principles of withdrawing water from a weir, or other management strategies can be stated by the auxiliary component.

2. Taipei Municipal Water Resources System Dynamics Model

A system dynamics model was built for the Danhsuei river watershed and used to evaluate the sustainability of water supply systems. The model is divided into several submodels, including two water supply systems for the Sindian and Dahan river and water demand submodels for three water supply districts, respectively. The model was developed in Vensim 4.0. The Sindian river system dynamics model is shown in Fig. 4. More detail descriptions of model development and other system dynamics models of the Danshuei river watershed and notations shown in Fig. 4 can be referred to Chen [13]

3. Validation Study

The water supply system dynamics model was verified whether it can reasonably provide predictions for the Sindian and Dahan river. In order to verify whether the proposed model can reasonably describe management strategies and reservoir operational rules, two sets of historical stream flows recorded in the period of 1991 through 1999 were used. The first set is inflows of the Feitsui and Shihmen reservoirs, and the second set is downstream flows. Upstream flows were input to the model to simulate downstream flows which were then compared with the observed flows recorded in the Hsiulung and Sanying bridge gauge stations for the Sindian and Dahan river, respectively. The results are shown in Figs. 5 and 6, which indicate the water supply system dynamics model can provide reasonable predictability.

Figure 5 shows there is a significant error on 96th month (i.e., October of 1998). The reason is that there was a strong typhoon with heavy rainfall to cause increased stream flows in this month. The system dynamics model developed in this study is lack of ability to describe reservoir operational rules for flood mitigation. Besides, the model assumes lateral flow proportional to its drainage area. The assumption may not be held for a typhoon event. If there are many typhoon events during simulation periods, the water supply system dynamics model may reduce its reliability. Further study to improve this weakness is required.

SUSTAINABILITY APPRAISAL

1. Sustainability Indicator

A sustainability indicator should be able to show the goal of sustainable development or the progress toward sustainability. Traditional indicators, such as the quantity of water demand and water supply, provide information, but any one alone is difficult to indicate sustainability. For example, a traditional indicator of water supply indicates that a water supply system can provide 3.0×10⁶ CMD. It is difficult to know whether or not it is sustainable, i.e. whether it is
Table 2. Sustainability of water supply systems (unit: 10^6 CMD)

<table>
<thead>
<tr>
<th>District</th>
<th>Current 1991-1999</th>
<th>Future 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Demand</td>
<td>Supply</td>
</tr>
<tr>
<td>Taipei</td>
<td>2.49</td>
<td>2.98</td>
</tr>
<tr>
<td>Banshin</td>
<td>0.57</td>
<td>0.62</td>
</tr>
<tr>
<td>Shihmen</td>
<td>0.66</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Note: *Simulated water supply is reduced due to water treatment capacity.

2. Results

Both current and future conditions are assessed. Current water demand is estimated based on 1991-1999 data, while future demand is projected for year 2025. This study estimates current demand and potential water supply for Taipei district are 2.49×10^6 and 2.98×10^6 CMD, respectively. In the year of 2025, if water leakage from distribution system can be improved, the projected water demand and supply are 2.63×10^6 and 3.32×10^6 CMD without considering possible climate change impacts. Both current and future carrying capacity of water supply can meet water requirements. The results show the water supply system of Taipei district is sustainable by the year of 2025. The value of n in Eq. 1 can be assigned to be 1.1, which indicates that the deficit of 10% of water supply is acceptable. The sustainability indicator for the water supply system of Taipei district is 1.0 for both current and year 2025. Table 2 indicates carrying capacities of water supply can meet water requirements in both Banshin and Shihmen districts also. This study assumes that the goal of improving water leakage has been achieved in the Taipei district. Besides, Banshin district can have water supply from Taipei district. The results may be seen as a vision for the Danshuei river watershed.

CONCLUSIONS

Water resources management is very important in Taiwan. Rainfall is not uniformly distributed in a year, which often results in flooding in humid seasons and drought in dry seasons. Sustainable water management requires quantitative information. A system dynamics model and an indicator were designed to appraise sustainability of water supply systems within the Danshuei river watershed. Simulation results indicate water demands do not exceed carrying capacities of water supply in Taipei, Banshin, and Shihmen districts under both current and future (2025) conditions. However, it does not imply there will be no water deficit, because the carrying capacity was determined based on the criterion of shortage index = 1. Besides, the conclusion can only be made when water loss of distribution system can be improved and Taipei dis-
This study intends to simulate a water resources system and assess its sustainability. Water management strategies and reservoir operational rules have been taken into account in the water supply system dynamics model. Although validation study verifies the model that provides reasonable simulation, more efforts should be done to improve the model. Water released from a reservoir is currently based on operational rules in the model. However, real operation may have different considerations. Water supply not only depends on available water in streams and capacities of water treatment, but also on water quality. In recent years, deficits of water supply due to poor water quality have been observed in Shihmen district. The studies on more realistic rules to determine release water from a reservoir and the impacts of water quality on water supply are suggested to improve simulation. Besides, climate change may impact on both water supply and water demand and further influence sustainability, which also needs to be considered in future studies.

REFERENCES


Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-Chief within six months of publication.

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