A study of water-land environment carrying capacity for a river basin

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Abstract The concept of driving force-state-response (DSR) framework was used to identify and develop the assessment model of water-land environment carrying capacity (WLECC) for a river basin. The river basin water-land management (RBWLM) decision support system was developed, based on the assessment model of WLECC, as a decision making tool. The Chung-Kang river basin, located in northern Taiwan, was used as a case study to generate a sustainable water-land management strategy. This strategy simultaneously derives the optimal solutions for land use management, water demand allocation, and water quality management. Furthermore, the sustainable WLECC can also be obtained. The WLECC can be used as the area-based indicator of sustainability to accurately measure the progress towards sustainable development for a river basin.

Keywords Sustainable development; water-land environment carrying capacity; driving force-state-response

Introduction

Recently, the term sustainable development has been coined. Sustainable development can be taken to mean evolution where some growth is permissible without reducing the resilience of natural, managed ecosystems, and socioeconomic systems. In addition, development ought to include improvement in the quality of life (Munn, 1992). Land use and water use are inseparable in a river basin water-land management. Almost everything that is done on the land affects the water resource environment in one way or another. Traditionally, land use and water management decisions have been made at different levels of government and/or agencies. The resulting conflicts and inconsistencies thus created are well known, but the progress in overcoming them has been slow (Viessman, 1990). Hence, to achieve the goal of sustainable development for a river basin, it is necessary to effectively protect and allocate the limited water and land resources. That is the water-land resources management, which includes the control of pollution and the allocation of water-land resources. In general, the goal of water-land resources management for a river basin is to maximize the total benefit of a water-land environment without reducing the resilience of water and land resources system (Chen et al., 1997). However, to ensure that the utilization of water-land resources will not affect moving towards sustainable development for a river basin, decision-makers at all levels (locally, regionally and nationally) need the information of water-land environment carrying capacity (WLECC). Therefore, the main purpose of this study is to define and develop the meaning as well as the assessment model of WLECC.

Definition of WLECC

In general, the idea of carrying capacity has its origins in biology. The term has been used there to indicate the maximum number of individuals of a particular species that can be supported by a given area (Ortolano, 1984) or the maximum number of individuals of a species
that can be sustained by an environment without decreasing the capacity of the environment to sustain that same amount in the future (Botkin and Keller, 1995). It can also be described as the population of a given species that can be supported indefinitely in a defined habitat without permanently damaging the ecosystem upon which it is dependent (Island Press, 1994). In addition, it can be interpreted as the maximum load, which can be exerted on a life support system by a population of animals, without damaging the system itself (Itn, 1995). In the environmental engineering field, the traditional concept of water quality management focuses on river assimilative capacity. This concept cannot be used to meet the requirement of water-land resources management of sustainable development. In other words, it does not simultaneously consider all the factors involved in water quality, water quantity, and land use of a river basin system (Chen et al., 1997). Although some definitions about the carrying capacity and assimilative capacity were proposed, they also can not meet the requirement of river basin water-land resources management.

The driving force-state-response (DSR) framework was adopted by the United Nations Commission on Sustainable Development (CSD) in 1995 as a tool for organizing information on Sustainable Development and for developing, presenting and analyzing indicators of Sustainable Development (Mortensen, 1997). Therefore, in this study, the concepts of DSR framework were used to address the causal relationships among the major components of a river basin system and to identify and develop the definition as well as the assessment model of WLECC. In general, the driving forces include human activities, processes and patterns that will have an impact on sustainable development. This impact can be both positive and negative. The states are the situation of the environment and natural resources, or a particular aspect of it, at a given point in time. This pertains to qualitative and/or quantitative description. The responses to changes in the state of sustainable development can be legislation, regulation, economic instruments, information activities etc. (UN, 1998 and Mortensen, 1997).

The top level water-land management was emphasized in this study. The activity of the management phase of top level management is strategic planning. Strategic planning emphasizes the development of overall goals of water-land management and methods for achieving them. In this study, a river basin system can be conceptually divided into some drainage zones based on the geographical characteristics. The principal components of a water-land environment system include the quantity and quality of water resources (surface water and ground water), land resources, and people and other aggregation which are related to the social and economic activities. The construction of each drainage zone is primarily based on a natural branch, natural tributary, or artificial discharger. It is assumed that each drainage zone withdraws water from the river and ground water. At the same time, the wastewater of each drainage zone is discharged into the river. The types of land use within each drainage zone can be conceptually divided into seven broad categories: residential and commercial land use, agricultural land use, industrial land use, forest land use, pasturage land use, protection or conservation land use, and other land use. Each land use type has its unit land use benefit, unit water demand, unit water use benefit, livestock and population densities, unit pollution loads of point and non-point sources, etc. The concept of land use categories is used to estimate the benefits of economic, social, and environmental objectives.

Sustainable development may be regarded as the progressive and balanced achievement of sustained economic development, improved social equity and environmental sustainability (Luxem and Bryld, 1997). Therefore, the overall objective of river basin water-land management in this study is to maximize the total benefit of economic, environmental, and social objectives under the conditions that utilization of water-land resources will not affect the sustainable development. To achieve this goal, three objectives, economic objective,
environmental objective, and social objective, are identified. To fulfil these three objectives, the specific aims, that is the driving forces, have been set: (1) economic objective—to maximize the land use benefit, to maximize the water use benefit, and to minimize the wastewater treatment cost; (2) environmental objective—to maximize the environmental quality; and (3) social objective—to maximize the population. The hierarchical structure of these objectives, the specific aims, and the effective measurements associated with the objectives are shown in Figure 1.

The conceptual model of water-land resources management for a river basin can be established based on Figure 1, as shown in Figure 2. Obviously, the causal relationships among driving forces, states, and responses can be identified. The objective of a river basin water-land management is not only to ensure that water-land resources can be sustainably used by the people and other aggregation on the river basin system, but also to maximize the total benefit of a river basin system as well as to conserve and protect water-land resources to avoid reducing the resilience of water environment. Hence, the overall objective of a river basin water-land resources management is to maximize the total benefit of a river basin system under resources, technology, law, and equity constraints. The constraints include suppliable water quantity and land area, waste load removal rate and water quantity allocation rate, water quality standards and land use standards, and equity. The definition of water-land environment carrying capacity (WLECC) can be given, based on the above demonstrations and identifications, as follows.

‘WLECC’ is defined as the optimum number of population equivalent which a river basin can support with a condition of pursuing the maximum benefit of an entire river basin and without decreasing the capacity to sustain the same amount in the future. This requires meeting the essential needs of the lives and activities for the people and other aggregation in the river basin system. Furthermore, activities related to the society and economy need to meet resource, technology, legal and equity constraints.

In short, the calculated carriable population equivalent number of a river basin system is the WLECC. WLECC can be used as the area-based indicator of sustainability to more accurately measure the progress towards sustainable development. Furthermore, WLECC can
be used as a resource constraint to ensure that the utilization of water and land resources will not affect the sustainable development of a river basin.

Assessment model of WLECC

The simplified assessment model of WLECC can be established based on its definition, the hierarchical structure and the conceptual model of water-land resources management for a river basin. The objective function represents the driving forces and the constraints represent the responses.

\[
\text{Max } Z = \sum_{i=1}^{n} \sum_{j=1}^{m_i} [W_E \cdot LU_{ij} \cdot D_{ij} + W_i \cdot S_{ij} \cdot D_{ij} + W_{E\text{nvir}} \cdot E\text{n}_{ij} \cdot D_{ij}] - \sum_{i=1}^{n} \sum_{j=1}^{l_i} W_E \cdot TC_{it} \cdot Z_{it}
\]

\[
+ \sum_{i=1}^{n} \sum_{j=1}^{u_i} W_E \cdot WU_{iu} \cdot O_{iu} \quad \text{--- driving forces}
\]

\[
\text{s.t.} \quad \sum_{i=1}^{n} \sum_{j=1}^{m_i} LU_{ij} \cdot D_{ij} \leq LU_{\text{U}} \quad i=1, \ldots, n \quad j=1, \ldots, m_i \quad \text{--- benefit constraint of land use}
\]

\[
\sum_{i=1}^{n} \sum_{a=1}^{u_i} WU_{iu} \cdot O_{iu} \leq WU_{\text{U}} \quad i=1, \ldots, n \quad u=1, \ldots, u_i \quad \text{--- benefit constraint of water use}
\]

\[
\sum_{i=1}^{n} \sum_{t=1}^{l_i} TC_{it} \cdot Z_{it} \leq TC_{\text{U}} \quad i=1, \ldots, n \quad t=1, \ldots, l_i \quad \text{--- cost constraint of wastewater treatment}
\]

\[
\sum_{i=1}^{n} \sum_{j=1}^{m_j} S_{ij} \cdot D_{ij} \leq SU \quad i=1, \ldots, n \quad j=1, \ldots, m_i \quad \text{--- benefit constraint of social objective}
\]

\[
\sum_{i=1}^{n} \sum_{j=1}^{m_j} E\text{n}_{ij} \cdot D_{ij} \leq E\text{NU} \quad i=1, \ldots, n \quad j=1, \ldots, m_i \quad \text{--- benefit constraint of environmental objective}
\]

\[
LLL_{ik} \leq L_{ik} \leq LUL_{ik} \quad i=1, \ldots, n \quad k=1, \ldots, 7 \quad \text{--- allocation rate constraint of land use}
\]
\[ E_{Lk} \leq E_{ik} \leq E_{ULk} \quad i=1,\ldots,n \quad k=1,\ldots,7 \] --- removal rate constraint of wastewater treatment

\[ A_{ik} \leq A_{ik} \leq A_{ULik} \quad i=1,\ldots,n \quad k=1,\ldots,7 \] --- allocation rate constraint of water use

\[ Q_i \leq Q_{ik} + Q_{IG} \quad i=1,\ldots,n \] --- water quantity standard

\[ DO_{ip} \geq DOST_{ip} \quad i=1,\ldots,n \quad p=1,\ldots,q_i \] --- water quality standard

\[ BOD_{ip} \leq BODST_{ip} \quad i=1,\ldots,n \quad p=1,\ldots,q_i \] --- water quality standard

\[ TN_{ip} \leq TNST_{ip} \quad i=1,\ldots,n \quad p=1,\ldots,q_i \] --- water quality standard

\[ TP_{ip} \leq TPST_{ip} \quad i=1,\ldots,n \quad p=1,\ldots,q_i \] --- water quality standard

where \( n \) is the total number of drainage zones or reaches; \( m_j \) is the option number of land use allocation, the social objective or the environmental objective in drainage zone \( i \); \( t_i \) and \( u_i \) are the option numbers of wastewater removal and water quantity allocation in drainage zone \( i \), respectively; \( W_E, W_S \) and \( W_{Envir} \) are the weight coefficients of the economic objective, the social objective and the environmental objective, respectively; \( LU_{ij}, WU_{iu} \) and \( TC_{it} \) are the land use benefit, the water use benefit and the wastewater removal cost of economic objective of options \( j, u \) and \( t \) in drainage zone \( i \), respectively; \( S_{ij} \) and \( EN_{ij} \) are the benefits of the social objective and the environmental objective of option \( j \) in drainage zone \( i \), respectively; \( D_{ij}, O_{iu} \) and \( Z_{it} \) are the land use decision variable, the water use decision variable and the wastewater removal decision variable of options \( j, u \) and \( t \) in drainage zone \( i \), respectively, whose value is one if the option is chosen and is zero otherwise; \( LUU, WUU \) and \( TCU \) are the land use benefit constraint, the water use benefit constraint and the wastewater removal cost constraint of the economic objective of options \( j, u \) and \( t \) in drainage zone \( i \), respectively; \( SU \) and \( ENU \) are the benefit constraints of the social objective and the environmental objective, respectively; \( L_{ik}, E_{ik} \) and \( A_{ik} \) are the land use allocation rate, the wastewater removal rate and the water quantity allocation rate of land use type \( k \) in drainage zone \( i \), respectively; \( LLL_{ik}, ELL_{ik} \) and \( ALL_{ik} \) are the minimal land use allocation rate, the minimal wastewater removal rate and the minimal water quantity allocation rate of land use type \( k \) in drainage zone \( i \), respectively; \( LUL_{ik}, EUL_{ik} \) and \( AUL_{ik} \) are the maximal land use allocation rate, the maximal wastewater removal rate and the maximal water quantity allocation rate of land use type \( k \) in drainage zone \( i \), respectively; \( Q_i \) is the water demand after allocation in drainage zone \( i \); \( Q_{ip} \) is the river flow rate in drainage zone \( i \); \( Q_{IG} \) is the supplyable ground water in drainage zone \( i \); \( DO_{ip}, BOD_{ip}, TN_{ip} \) and \( TP_{ip} \) are the DO, the BOD, the TN and the TP concentrations of check point \( p \) in drainage zone \( i \), respectively; \( DOST_{ip}, BODST_{ip}, TNST_{ip} \) and \( TPST_{ip} \) are the DO, the BOD, the TN and the TP standards of drainage zone \( i \), respectively.

The above optimization model is a zero-one integer programming model, which can be solved using bound implicit enumeration (BIE) algorithm. The BIE algorithm (Chang and Liaw, 1987), a modified implicit enumeration algorithm, performs systematic searching and eliminates combinations of options with an upper bound and a lower bound in the process of finding the optimal solution. However, the original BIE algorithm has a disadvantage. That is, it always re-simulates in the searching process of each searching run. Therefore, a modified BIE algorithm is proposed in this study, which can be used to solve the formulated assessment model of WLECC. A memory method of the variables of each stage is added into the original BIE algorithm. The memory method of variables of each stage was developed to memorize the simulation results of each variable of each stage so as
to avoid re-simulating in the searching process of each searching run. The proposed method can be used to enhance the searching efficiency.

In the computerized solving procedure of WLECC assessment model, to each of the objectives was assigned a weight so that the objectives could be combined into a single objective function. The final goal of WLECC model is then to maximize the total benefit of three main objectives, namely, economic, environmental, and social objectives. A river basin water-land management system can be treated as a multistage multi-option system, and each stage may contain several options. Furthermore, in each stage, only one option can be selected for system synthesis. There are three main objectives (economic, environmental, and social objectives) for each drainage zone of a river basin system. The economic objective involves three sub-objectives, namely, land use, water use, and wastewater treatment. Therefore, a land use allocation combination of each drainage zone is accompanied by both a social objective value and an environmental objective value. The combination numbers of each drainage zone are obtained by multiplying the option numbers of land use allocation rate, the option numbers of the water quantity allocation rate, and the option numbers of the wastewater removal rate. Furthermore, the total combination of an entire river basin is obtained by multiplying the combination numbers of each drainage zone of a river basin system.

River basin water-land management (RBWLM) decision support system was developed based on the assessment model of WLECC and on the conceptual model of water-land resources management for a river basin. The system was built, based on the modification of RBWLM decision support system (Chen et al., 1997), using integration of Microsoft Visual Basic, Microsoft Excel, Microsoft Access, and ARC/INFO software. RBWLM is composed of an information management subsystem, a model management subsystem, and a decision-making subsystem. The RBWLM system can be used to generate, based on different driving forces and responses, a sustainable water-land management strategy, including land use allocation, water quantity allocation, and pollution abatement in each drainage zone of a river basin. The WLECC of the sustainable strategy can be also obtained by the system.

Case study
The Chung-Kang river basin, which located in northern Taiwan, has an area of 445.58 km² and the total length of this river is 54.14 km. The basin can be conceptually divided into 13 drainage zones based on the geographic characteristics. According to the development

### Table 1 Land Use Combinations of the Multi-Objective Sustainable Solution

<table>
<thead>
<tr>
<th>Zone</th>
<th>Residential/Commercial Land Use (ha)</th>
<th>Industrial Land Use (ha)</th>
<th>Agriculture Land Use (ha)</th>
<th>Forest Land Use (ha)</th>
<th>Pasturage Land Use (ha)</th>
<th>Protection Land Use (ha)</th>
<th>Other Land Use (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>326.73</td>
<td>206.42</td>
<td>701.78</td>
<td>4396.55</td>
<td>0</td>
<td>116.34</td>
<td>280.19</td>
</tr>
<tr>
<td>Zone 2</td>
<td>510.19</td>
<td>498.27</td>
<td>918.64</td>
<td>7813.47</td>
<td>0</td>
<td>62.82</td>
<td>440.61</td>
</tr>
<tr>
<td>Zone 3</td>
<td>140.95</td>
<td>184.56</td>
<td>473.21</td>
<td>510.84</td>
<td>0</td>
<td>11.2</td>
<td>75.23</td>
</tr>
<tr>
<td>Zone 4</td>
<td>1459.28</td>
<td>1296.36</td>
<td>4020.47</td>
<td>3300.75</td>
<td>182.68</td>
<td>241.11</td>
<td>246.57</td>
</tr>
<tr>
<td>Zone 5</td>
<td>60.95</td>
<td>90.11</td>
<td>268.86</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>70.08</td>
</tr>
<tr>
<td>Zone 6</td>
<td>22.10</td>
<td>22.16</td>
<td>49.96</td>
<td>108.22</td>
<td>0</td>
<td>0</td>
<td>9.56</td>
</tr>
<tr>
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<td>408.95</td>
<td>141.02</td>
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<td>118.52</td>
<td>0</td>
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<td>61.58</td>
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<tr>
<td>Zone 8</td>
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<td>608.26</td>
<td>198.34</td>
<td>16.19</td>
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<td>98.16</td>
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<td>1198.71</td>
<td>3014.28</td>
<td>2008.32</td>
<td>183.59</td>
<td>331.55</td>
<td>563.14</td>
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<td>631.87</td>
<td>702.63</td>
<td>70.06</td>
<td>92.55</td>
<td>57.20</td>
<td>26.54</td>
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<tr>
<td>Zone 11</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>20.69</td>
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<tr>
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<td>285.44</td>
<td>702.38</td>
<td>96.98</td>
<td>98.33</td>
<td>52.76</td>
<td>128.40</td>
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<td>Zone 13</td>
<td>1993.09</td>
<td>388.79</td>
<td>385.23</td>
<td>0</td>
<td>8.52</td>
<td>0</td>
<td>246.36</td>
</tr>
</tbody>
</table>
requirement in the year 2020 for the Chung-Kang river basin, the total number of possible combinations, which include the land use allocation rate, the water quantity allocation rate, and wastewater treatment rate of the river basin is about. The weighting method of multi-objective programming and the modified BIE algorithm were used to generate a multi-objective sustainable water-land management solution. The weight of each objective was assigned to be one. The solution, shown in Table 1 and Table 2, indicates the optimal land use combinations, water use allocations, and water quality management for all drainage zones. In the solution, the total benefit of the entire river basin is about NT$ /day. The suggested WLECC of the Chung-Kang river basin can be used as a reference for promoting sustainable development of water-land resources.

Conclusions
The definition and assessment model of WLECC have been identified and established based on the concept of DSR framework. The RBWLM can be used to generate a sustainable water-land management strategy, including land use allocation, water quantity allocation, and pollution abatement in each drainage zone of a river basin. In addition, the river water quality, the total benefit, the benefit of each objective, and the WLECC can be obtained. The calculated WLECC can be used as the area-based indicator of sustainability to more accurately measure the progress towards sustainable development. Furthermore, the WLECC can be used as a resource constraint to ensure that the utilization of water and land resources will not affect moving towards sustainable development of a river basin. The assessment model of WLECC for a river basin overcomes many of the difficulties and limitations of traditional concepts, such as the assimilative capacity, carrying capacity, and environmental capacity.

Acknowledgements
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References

Table 2 Results of the Multi-objective Sustainable Solution

<table>
<thead>
<tr>
<th>Zone</th>
<th>Water Demand (CMD)</th>
<th>Wastewater removal rate</th>
<th>Permissible waste loads (kg/day)</th>
<th>Population number</th>
<th>WLECC (population equivalent)</th>
</tr>
</thead>
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<td>Zone 1</td>
<td>82140.47</td>
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<td>135.62</td>
<td>31542</td>
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