Evaluation of reuse potential of industrial wastewater treatment plant effluent based on quality and quantity using grey relation analysis

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Abstract

In this study, the effluent reuse potential of 39 industrial wastewater treatment plants (WWTPs) in Taiwan was evaluated using grey relation analysis. A significant, consistent result was revealed. The WWTPs with the lowest reuse potential among 39 industrial parks were in the order: Gueishan, Tucheng, Nankang WWTPs. The WWTPs with highest reuse potential were as follow: Yungan > Tafa > Fongshan. The lowest reuse potential WWTP was Gueishan and the highest one was Hsinchu Technology in northern Taiwan. In central Taiwan, the potential of Nankang WWTP was the lowest, while the potential of Changpin was the highest. The lowest reuse potential WWTP was Jenta (ocean discharge) and the highest one was Yungan in southern Taiwan. In eastern region of Taiwan, the reuse potential of Lungte was higher, that of Guanghwa was lower. The better and larger a WWTP’s effluent quality and quantity were, the higher reuse potential of that WWTP was. But the quantity did not affect the potential significantly.

Keywords: Reuse potential; industrial wastewater treatment plant; effluent; quality; quantity; grey relation analysis
INTRODUCTION

Because the population increase and business, industries develop in Taiwan, the water demand increases significantly. But it is difficult to seek a new water resource because of rare new dam sites, serious polluted river water and excess water usage. In this situation, reclaimed water reuse becomes an important issue.

In general, reclaimed water reuse includes storage of rain water, recycle and reuse of municipal wastewater, industrial wastewater, agriculture irrigation water etc. About 25% of worldwide water demand is related to industrial applications (Asano, 1998). If the industrial wastewater can be reclaimed, reused and recycled appropriately, it will be helpful to overcome the problem of water shortage.

Overview of the industrial development in Taiwan, more than 80 industrial parks were developed, the numbers of public industrial parks are 39 (11 parks in northern, 9 in central, 17 in southern and 2 in eastern region). In these industrial parks, self-operation and secondary biological treatment are adopted in their wastewater treatment plants (WWTPs). If the reuse potential of the WWTP effluent can be evaluated appropriately, as the reference of reuse in the future, the problem of water shortage can be solved.

There are many factors to be considered when evaluating the wastewater reuse potential including effluent water quality, quantity, space for installing reclaiming equipment etc. Among these factors, wastewater quality and quantity for reuse were the most important consideration (Tchobanoglous and Angelakis, 1996; Bonomo et al., 1999; Mujeriego and Asano, 1999; Visvanathan and Cippe, 2001). Due to the fact that many factors shall be considered in wastewater evaluation, it is suggested to adopt an appropriate method to best present a complete and informational data. In order to evaluate the complete wastewater reuse potential and gain consistent results from the monitoring data, the grey system theory (GST) is an applicable method.

In system theories, a complete degree of information is often described by the shade of colors. Grey means incomplete or uncertain information. According to GST, any random process is regarded as a grey process. The GST proposed by Deng (1982) can resolve the problem of incomplete information and data and has gained many significant and effective results.
(Chang et al., 2007; Pai et al., 2007 a, b, c; 2008 a, b, c; Pai 2008). Overall speaking, system behavioral data often does not follow a particular pattern and it changes unpredictably according to its circumstances. For this kind of dispersed data, regression analysis or mathematical statistics are most commonly used to analyze them. The downside of this method is that it requires a very large sum of data and all data must be within normal distribution. If in any case some or all of the data don’t fall into normal distribution or if there is not sufficient amount of data, functions will not be correctly calculated and this statistical summary will not lead to a research end result. On contrary, GST requires only a small amount of data to be effective. It focuses on the relational analysis, model construction, and prediction of the indefinite and incomplete information.

There are many analysis methods in GST. Grey relational analysis (GRA) can be used to deal with the system with partially unknown information and can be used to determine the relationship between different sequences of data. In environmental management, there were many environmental indexes and monitoring data. If the significant variation trend could be evaluated, a better control strategy could be sought. Hence GST was used to explore the reuse potential of Taiwan’s 39 industrial wastewater treatment plant effluent based on effluent quality and quantity.

The objectives of this study are listed as follows. (1) Investigate the nationwide wastewater effluent quality of 39 industrial WWTPs in Taiwan. (2) Utilize the GRA to evaluate the reuse potential of 39 industrial WWTPs.

MATERIALS AND METHODS

2.1. Data collection

The data from 39 industrial WWTPs regulated by the local environmental protection bureau were collected. In Taiwan, if the effluent comes from the designated sewers of industrial parks or other industries, only four effluent characteristics, i.e., suspended solids (SS), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and true color, were regulated according to Effluent Standard. So, the items included SS, BOD, COD and quantity.

2.2. Grey relation analysis

GRA is one of the research topics of GST. Its aim is to explore and
investigate the factors that cause the problems of the system and use it as the mean to find the answers to the problems. The analytical method is based on finding the relationships of both independent and interrelating data series of the problem. By exercising the GRA mathematically, the Grey Relation Grade (GRG) can be used to evaluate the relational level between referential series and each comparative series, to distinguish which area has a more serious problem of contamination. The algorithm of GRA is illustrated as following.

In grey relational space, there is a referential series with k entities described as:

\[ X_0(k), k = 1, 2, \ldots, n \]

In this study, the Effluent Standard shown in Table 1 and the minimum flowrate among 39 industrial WWTPs were adopted as the referential series. So \( n \) was equal to 4 when calculating GRGs.

There are also \( m \) comparative data series with k entities described as:

\[ X_i(k), i = 1, 2, \ldots, m; k = 1, 2, \ldots, n \]

Since there were 39 industrial WWTPs discussed in this study, \( m = 39 \) when calculating GRGs. That is

\[
\begin{align*}
X_0 &= (x_0(1), x_0(2), \ldots, x_0(n)) \\
X_1 &= (x_1(1), x_1(2), \ldots, x_1(n)) \\
X_2 &= (x_2(1), x_2(2), \ldots, x_2(n)) \\
& \quad \vdots \\
X_m &= (x_m(1), x_m(2), \ldots, x_m(n))
\end{align*}
\]

Before calculating the grey relational coefficients (GRCs), theses series data can be dealt depended on the following three kinds of situation. Three types of pre-processing are available:

(1) Normalized by maximum value (upper-bound effectiveness measuring, i.e., larger-the-better)

\[
x_i^*(k) = \frac{x_i(k) - \min_{v_j} x_j(k)}{\max_{v_k} x_k(k) - \min_{v_k} x_k(k)}
\]  

(1)
where \( \max_{i \in k} x_i(k) \) is the maximum value of entity \( k \) and \( \min_{i \in k} x_i(k) \) is the minimum value of entity \( k \).

(2) Normalized by minimum value (lower-bound effectiveness measuring, i.e., smaller-the-better)

\[
x_i^*(k) = \frac{\max_{i \in k} x_i(k) - x_i(k)}{\max_{i \in k} x_i(k) - \min_{i \in k} x_i(k)}
\]

(3) Normalized by objective value (moderate effectiveness measuring, i.e., nominal-the-better)

\[
x_i^*(k) = 1 - \frac{|x_i(k) - x_{ob}(k)|}{\max_{i \in k} \left( \max_{i \in k} x_i(k) - x_{ob}(k), x_{ob}(k) - \min_{i \in k} x_i(k) \right)}
\]

where \( \max_{i \in k} x_i(k) \) and \( \min_{i \in k} x_i(k) \) are also the same definition in Equation (1) and Equation (2), \( x_{ob}(k) \) is the objective value of entity \( k \).

A smaller pollutant concentration value and a larger flowrate represented better reuse potential, hence the normalized by minimum value and normalized by maximum value were adopted for pre-processing of effluent quality and quantity respectively when calculating GRGs.

The GRC between the comparative series \( X_i \) and the referential series \( X_0 \) at the \( k \)-th entity is defined as (Wong and Lai, 2000):

\[
r_{0i}(k) = \left( \frac{\Delta \text{Min} + \Delta \text{Max}}{\Delta_{0i}(k) + \Delta \text{Max}} \right)^5
\]

where \( \Delta_{0i}(k) \) is the absolute value of difference between \( X_0 \) and \( X_i \) at the \( k \)-th entity, that is

\[
\Delta_{0i}(k) = |x_0(k) - x_i(k)|
\]

and

\[
\Delta_{\text{Min}} = \min_{j \in i} \min_{k} |x_0(k) - x_j(k)|
\]
\[
\Delta_{\text{max}} = \max_{j \in I, k} \| x_0(k) - x_j(k) \|
\]

(7)

\( \varepsilon \in [0, 1] \) is the distinguishing coefficient to control the resolution between \( \Delta_{\text{max}} \) and \( \Delta_{\text{min}} \), typically taken as 0.5.

The GRG for series \( X_i \) is given as:

\[
r(X_0, X_i) = \frac{1}{n} \sum_{k=1}^{n} \left( \frac{\Delta_{\text{Min}} + \Delta_{\text{Max}}}{\Delta_{ij}(k) + \Delta_{\text{Max}}} \right)^{\varepsilon} = \frac{1}{n} \sum_{k=1}^{n} r_{ij}(k)
\]

(8)

Once GRG was calculated, the GRG could be used to evaluate the reuse potential.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>30</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>COD</td>
<td>100</td>
<td>mg L(^{-1})</td>
</tr>
<tr>
<td>SS</td>
<td>30</td>
<td>mg L(^{-1})</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSION**

This study collected the monitoring data regulated by the EPB, as shown in Table 2 (column 1 to column 5). All treated effluent met the Effluent Standard of Taiwan. Then the data was analyzed per industrial park using GRA. The calculation was divided into two parts, first part was calculated using present flowrate (column 5 in Table 2), and it represented the present reuse potential. The second part was calculated using the designed maximum flowrate (column 4 in Table 2), and it represented the maximum reuse potential in the future. The GRG that are closer to 0 indicate a worse reuse potential which means that the effluent quality of that WWTP is worsen and quantity is less; WWTP with grade close to 1 represents a better potential. All the calculated results were shown in Table 2 (column 6 to column 7).

**3.1. Validation of TWEA1**

According to Table 2 (column 7), the WWTPs with the lowest reuse potential among 39 industrial parks were in the order: Gueishan, Tucheng, Nankang WWTPs. Their GRGs were 0.784765, 0.784986 and 0.785348
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respectively. The WWTPs with highest reuse potential were as follow: Yungan > Tafa > Fongshan. Their GRGs were 0.786735, 0.786725 and 0.786722 respectively.

Table 2 Effluent quality, quantity and calculated GRGs of 39 industrial WWTPs

<table>
<thead>
<tr>
<th>Industrial Parks</th>
<th>Items of effluent quality</th>
<th>Quantity</th>
<th>GRGs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOD (mg L⁻¹)</td>
<td>COD (mg L⁻¹)</td>
<td>SS (mg L⁻¹)</td>
</tr>
<tr>
<td><strong>Northern</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tawulun</td>
<td>30</td>
<td>23.7</td>
<td>16.5</td>
</tr>
<tr>
<td>Wugu</td>
<td>18.5</td>
<td>43.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Tucheng</td>
<td>27.1</td>
<td>93.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Gueshan</td>
<td>12</td>
<td>111</td>
<td>63</td>
</tr>
<tr>
<td>Dayan</td>
<td>1.4</td>
<td>8.3</td>
<td>16.4</td>
</tr>
<tr>
<td>Guanyin</td>
<td>11.3</td>
<td>61.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Zhongli</td>
<td>13</td>
<td>78.7</td>
<td>18.0</td>
</tr>
<tr>
<td>Pinghe</td>
<td>14</td>
<td>85.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Taoyuan Youth</td>
<td>23</td>
<td>65.7</td>
<td>18.7</td>
</tr>
<tr>
<td>Hsinchu</td>
<td>4.5</td>
<td>44.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Hsinchu Technology</td>
<td>9.6</td>
<td>24.3</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nankang</td>
<td>21.5</td>
<td>83.1</td>
<td>21.1</td>
</tr>
<tr>
<td>Tainhuang Youth</td>
<td>5</td>
<td>98.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Taichung</td>
<td>4.8</td>
<td>52.2</td>
<td>7.9</td>
</tr>
<tr>
<td>Dali</td>
<td>20.1</td>
<td>40.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Fangyuan</td>
<td>5</td>
<td>54.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Changpin</td>
<td>1.8</td>
<td>28.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Chuan-Hsing</td>
<td>2</td>
<td>63.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Douliou</td>
<td>6</td>
<td>67.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Yun-lin Technology</td>
<td>30</td>
<td>20.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Southern</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mintsoog</td>
<td>7.6</td>
<td>38.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Cha-Tai</td>
<td>4.4</td>
<td>78.2</td>
<td>7.1</td>
</tr>
<tr>
<td>Sinying</td>
<td>2.4</td>
<td>98.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Guangtian</td>
<td>3</td>
<td>71.2</td>
<td>15.8</td>
</tr>
<tr>
<td>Yongkang</td>
<td>7.4</td>
<td>38.2</td>
<td>5.4</td>
</tr>
<tr>
<td>Anping</td>
<td>7</td>
<td>67.0</td>
<td>6.0</td>
</tr>
<tr>
<td>South Technology</td>
<td>12.2</td>
<td>33.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Tainan Technology</td>
<td>5.8</td>
<td>34.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Yungan</td>
<td>3</td>
<td>16.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Tafa</td>
<td>1</td>
<td>31.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Fongsan</td>
<td>4.8</td>
<td>19.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Linyuan</td>
<td>9.5</td>
<td>80.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Linhai</td>
<td>4</td>
<td>35.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Jenta</td>
<td>2.8</td>
<td>83.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Jenta (ocean discharge)</td>
<td>8.8</td>
<td>75.9</td>
<td>18.0</td>
</tr>
<tr>
<td>Pingnan</td>
<td>7.1</td>
<td>62.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Neipo</td>
<td>11</td>
<td>34.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Eastern</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lungte</td>
<td>2.4</td>
<td>34.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Guanghwa</td>
<td>30</td>
<td>25.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>
If Taiwan was divided into four parts, i.e., northern, central, southern and eastern regions, it showed that the lowest reuse potential WWTP was Gueishan and the highest one was Hsinchu Technology at northern Taiwan. Their GRGs were 0.784765 and 0.786502 respectively. In central Taiwan, the potential of Nankang WWTP whose GRG was 0.785348 was the lowest, the potential of Changpin with a GRG value of 0.786708 was the highest. The lowest potential was Jenta (ocean discharge) and the highest one was Yungan in southern region. Their GRGs were 0.785995 and 0.786736 respectively. There were only two parks in eastern region of Taiwan. The GRG of Lungte was higher, its value was 0.785697; the GRG of Guanghwa was lower, its value was 0.786544.

The results indicated that the better and larger a WWTP’s quality and quantity were, the higher reuse potential of that WWTP was. But the quantity did not affect the potential absolutely.

3.2. Designed flowrate

The designed flowrate (column 4 in Table 2) of each WWTP was used to evaluate the maximum reuse potential in the future. According to Table 2 (column 6), the WWTPs with the lowest reuse potential among 39 industrial parks were the same as those calculated using present flowrate, i.e., Gueishan, Tucheng, Nankang WWTPs. The WWTPs with highest reuse potential were as follow: Yungan > Tafa > Fongshan.

The lowest reuse potential WWTP was Gueishan and the highest one was Hsinchu Technology in northern Taiwan. In central Taiwan, the potential of Nankang WWTP was the lowest, while the potential of Changpin was the highest. The lowest reuse potential WWTP was Jenta (ocean discharge) and the highest one was Yungan. In eastern region of Taiwan, the GRG of Lungte was higher, the GRG of Guanghwa was lower.

The results indicated that the better and larger a WWTP’s quality and quantity were, the higher reuse potential of that WWTP was. But the designed flowrate did not affect the potential absolutely too.

In the study proposed by Tchobanoglous and Angelakis (1996), SS and BOD were also investigated to assess wastewater reuse potential in Greece. They indicated that almost all of the effluent can be used without additional treatment for irrigation. He et al. (2001) assessed the wastewater reuse potentiality based on the statistics investigation and some realized reuse
projects. They found that the volume of reclaimed water for industrial reuse was 1.2355 -106 m3 d in China in 1996. Additionally, 55% amount of industrial water consumption could be supplied by reclaimed water. Barbagallo et al. (2001) divided total Italy into northern, central and southern regions, and discussed wastewater reuse in these three regions and total Italy. They found that wastewater reuse for agricultural purposes were the most attractive option between different reuse applications in Italy. But in the studies described above, the wastewater quality and quantity were evaluated separately. In this study, GRA was adopted to evaluate whole and individual reuse potential of industrial WWTPs. A significant, consistent result was revealed.

**CONCLUSIONS**

In this study, the wastewater reuse potential was evaluated using GRA and a significant, consistent result was revealed.

In Taiwan, the WWTPs with the lowest reuse potential among 39 industrial parks were in the order: Gueishan, Tucheng, Nankang WWTPs. The WWTPs with highest reuse potential were as follows: Yungan > Tafa > Fongshan.

The lowest reuse potential WWTP was Gueishan and the highest one was Hsinchu Technology in northern Taiwan. In central Taiwan, the potential of Nankang WWTP was the lowest, while the potential of Changpin was the highest. The lowest reuse potential WWTP was Jenta (ocean discharge) and the highest one was Yungan in southern region. In eastern region of Taiwan, the reuse potential of Lungte was higher, Guanghwa was lower.

The better and larger a WWTP’s effluent quality and quantity were, the higher reuse potential of that WWTP was. But the quantity did not affect the potential significantly.

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parameters. Environmental Monitoring and Assessment, 146 (1-3), 51-66.


基於工業區廢水廠出流水水質水量之再利用潛勢灰關聯評估

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摘 要

本研究針對工業區廢水處理廠，利用灰色系統內之灰關聯分析法（Grey relational analysis）評估各工業區廢水再生利用之潛勢。分析項目中，放流水水質經望小前處理，而放流水水量經望大前處理，灰關聯度值越大表示越具水再生利用之潛力，越小表示越不具水再生利用之潛力。分析結果顯示，台灣地區最不具水再生利用潛力之工業區依序為龜山工業區、土城工業區、南崗工業區，而最具水再生利用潛力之工業區依序為永安工業區、大發工業區、鳳山工業區；北部以新竹科學園區最具水再生利用之潛力；中部以彰濱（線西）工業區最具水再生利用之潛力；南部以永安工業區最具水再生利用之潛力；東部以龍德工業區最具水再生利用之潛力，其皆為水質較良好之地區，因此具有回收之潛力。本研究之相關結果可供工業區水再生利用評估之參考。

關鍵詞：工業區廢水廠，水質，水量，再利用潛勢，灰關聯