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The Study of Land Subsidence Disaster Prevention by Water Resource Exploitation and Groundwater Recharge — A Case of Changhua and Yunlin Regions, Taiwan

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Owing to the hydrological difference between the wet and dry seasons and having no existing large-scale water storage facilities to allocate water quantities in Changhua and Yunlin regions, large percentages of water demands are supplied by groundwater. Therefore, yearly, water resources are overloaded and the groundwater level is in decline, leading to severe land subsidence in those regions. Because of an imbalance between the supply and demand of water resources, most water supplies depend on groundwater. Consequently, it is impossible to immediately implement a well plugging plan to reduce over pumping. In order to respond to the severity of land subsidence, the study found several methods to solve the complex problem of water resource exploitation and utilization by the D-S-R (Driving force — Status — Response) analysis and has also selected the plans and areas suitable for implementing groundwater recharge via a five-criteria selection process. Finally, the goal of this study is to help increase the quantity of surface water supply and groundwater recharge as well as retard land subsidence and its associated disasters in Changhua and Yunlin regions.

Keywords: Water resource exploitation; Groundwater recharge; Land subsidence.

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1. Background

1.1. *The environmental description of Changhua and Yunlin counties*

Changhua and Yunlin are two counties located in central western Taiwan. Wu River and Pe-Kang River is the northern boundary of Changhua County and the southern boundary of Yunlin County, respectively, while Chou-Shui River is the border that separates these two counties. The population is 2 million, and the majority of land property is agriculture. But some important industrial parks were developed recently such as the Coastal Industrial Park in Yunlin County and Chung-hua Coastal Industrial Park in Changhua County. Rainfall of this area is mostly centralized during the wet season, from May to October. According to statistical data of recent years, the average accumulated rainfall is 2,019 mm in Changhua (1946–2009), and 2,211 mm in Yunlin (1923–2009) (Water Resource Agency, 2010). The hydrogeology of this area is recent alluvium named Chou-Shui River Alluvial Fan which is the kind of hydrogeological type with the most abundant groundwater resource (Water Resources Planning Commission, 1986). Figure 1 shows the geological location of Changhua and Yunlin counties in Taiwan and the relationship between these two counties and the Chou-Shui River Alluvial Fan.

1.2. *Water resources utilization condition*

From the water usage quantities for human consumption, agriculture, and industry, the water resources utilization condition can be known for the study area. The statistical data of 2002–2008 showed that the annual per capita water consumption was 113.259 tons; the average water usage for industry was 0.316 tons; and for agriculture was 3.712 tons. In agricultural water usage, there were 3.146 billion tons per year for irrigation, 0.036 for animal husbandry, and 0.53 for cultivation (Consumptive Water Statistics Database, WRA). From these data we can know that the agricultural water usage has the most percentage, 87%, of the total water demand.

1.3. *Land subsidence condition*

According to the measured data of surface level by the Water Resource Agency during June 2008 to July 2009, the townships that have a yearly subsidence rate larger than 3 cm/yr in Changhua County include Sihu, Fangyuan, Jhutang, Pitou, Sijhou and Erlin. The largest subsidence rate is 5.7 cm/yr and the ongoing subsidence area includes 78 km^2. The major subsidence areas are located on the central boundry between Erlin and Fangyuan, northern Sihu, and the boundry between Sijhou and Pitou, which all have a yearly subsidence rate greater than 5 cm/yr. In Yunlin, the townships that have a yearly subsidence rate greater than

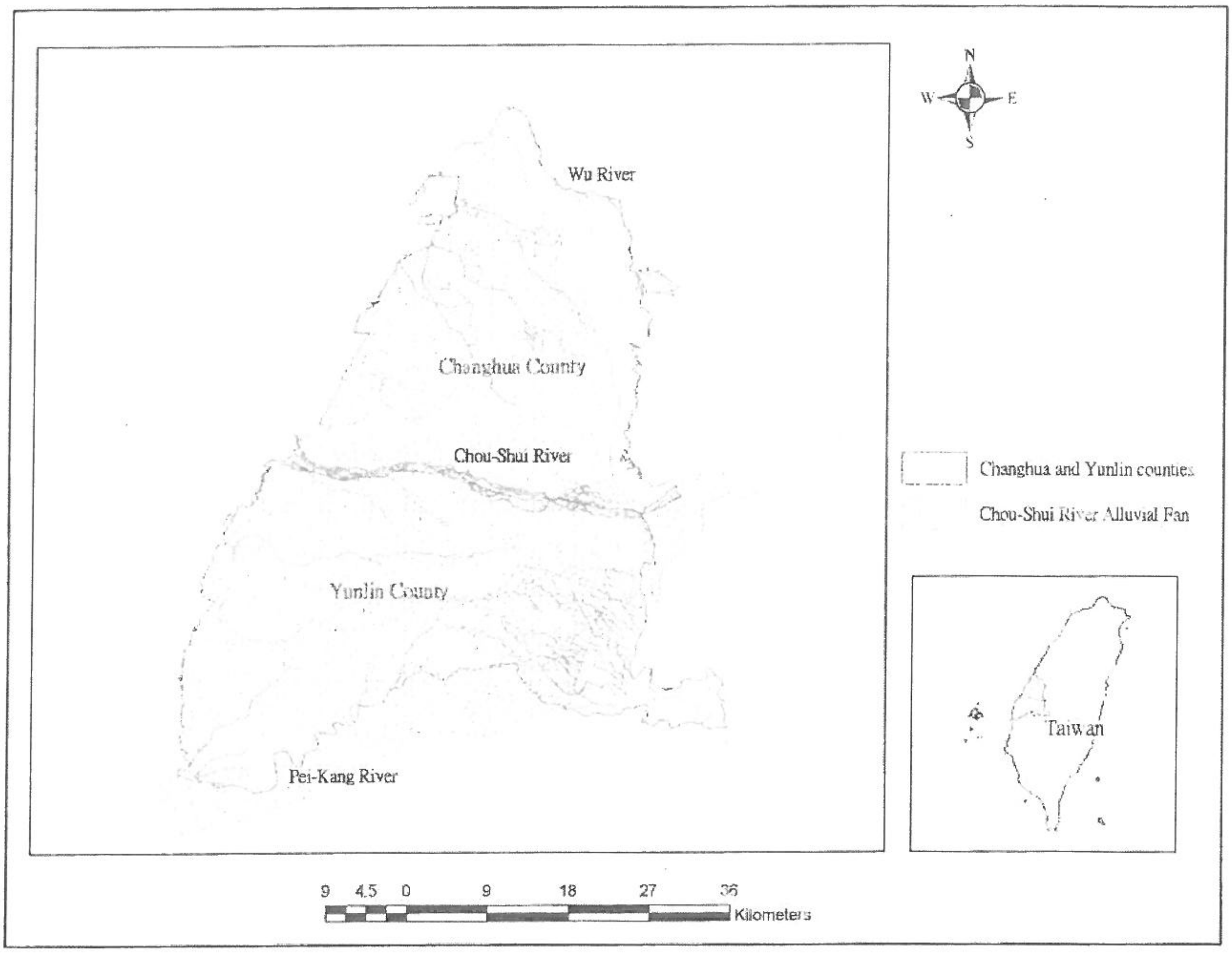

Figure 1 Geological location of Changhua and Yunlin counties.

3 cm/yr include Erlun, Huwei, Tuku, Yuanchang, Baojhon, Lunbei, Dongshih, Mailiao, Taisi, Sihhu, Kouhu, Shueilin, Dapi, Dounan and Beigang. The largest yearly subsidence rate 7.4 cm/yr occurred in Huwei (Land Subsidence Database, WRA).

According to the information regarding severe land subsidence areas announced by the Ministry of Economic Affairs in 2005, some whole townships are completely subsiding such as Dacheng in Changhua County and Mailiao, Taisi, Kouhu, Tuku, Yuanchang and Shueilin in Yunlin County. In other townships, only partial areas are severely subsiding, which include Fangyuan in Changhua County and Lunbei, Baojhon, Huwei, Dongshih, Dapi and Beigang in Yunlin County (Figure 2).

2. Research Methods

2.1. *Literature review*

The supply and demand imbalance of water resources followed in the wake of industrial development leading the condition of land subsidence to worsen due to

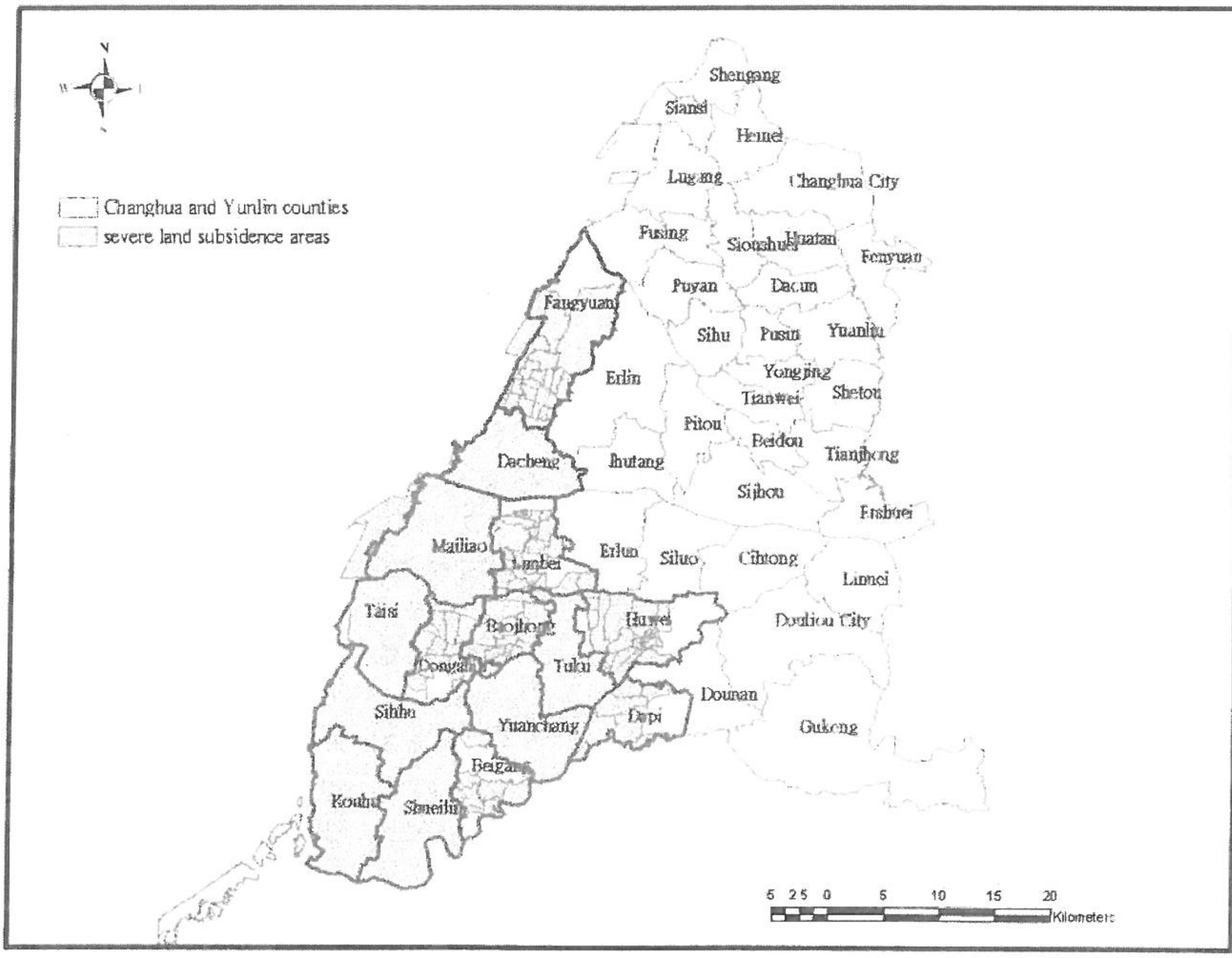

Figure 2 Land subsidence condition in Changhua and Yunlin counties.

over pumping of groundwater. So this study is expected to clarify the development and usage trends of water resources for the future. In order to meet the principles of sustainability, this study adopts the development framework and system thinking of the sustainable indicator system, the D-S-R method, which was developed by the United Nations. Besides, this study is expected to clarify and solve the problem of local water and soil resources in the criterion of sustainable development.

The framework of sustainable indicators was originally created as P-S-R (Pressure-State-Response) by the OECD (Organization for Economic Co-operation and Development) in 1993, and then the P-S-R system was revised to the D-S-R (Driving force-State-Response) system by the UN in 1997.

According to the current definition of the D-S-R system that was made by the UN, the Driving force represents positive and negative influences on sustainable development that include human's behavioral processes and types impacting the environment; the State represents the condition of sustainable development; the Response represents each activity that conforms to sustainable development (UNDSD, 2001). It can show the state of the living environment (State), the reasons that cause the state of the environment (Driving force), the activities that humans use to conform to sustainable development, and the reciprocal effect of each item.

The framework of D-S-R can show the concept of management, in other words, it can show the problem that influences sustainable development and push for controlled strategic programs to sustain the environment through continual feedback. Presently there are many countries that use the D-S-R framework program for evaluating society, economics, and the environment. The D-S-R system can provide enough suitable information to manage those areas. As far as we know, no one has used this method for solving land subsidence.

2.2. D-S-R analysis

We used the D-S-R (UNCSD, 1996) analysis to evaluate the water resource developmental possibilities in Changhua and Yunlin counties with the principle of sustainability. "D" means driving force, "S" means state, and "R" means response. Driving force means actions which would impact or affect the environmental resource state for people's living and life such as the population growth, social development and economic activities, including commerce, industry and agriculture. State means the water resource condition after the development actions, policies or strategies are carried out, or the state of quality and quantity of water resources that could be utilized. Response means water resource development and management policies, strategies, methods or measures for changing the water resources state (better or worse) provided by the government or relative organizations such as the water resource white book, local development strategy, water resource utilization strategy, and water quantity allocation measures. The D-S-R analysis system in this study is shown in Figure 3.

We also used five criteria including water source type, recorded water source condition, future water source utilization condition, restricted condition, and sustainable utilization strategy to evaluate water utilization problems in Changhua

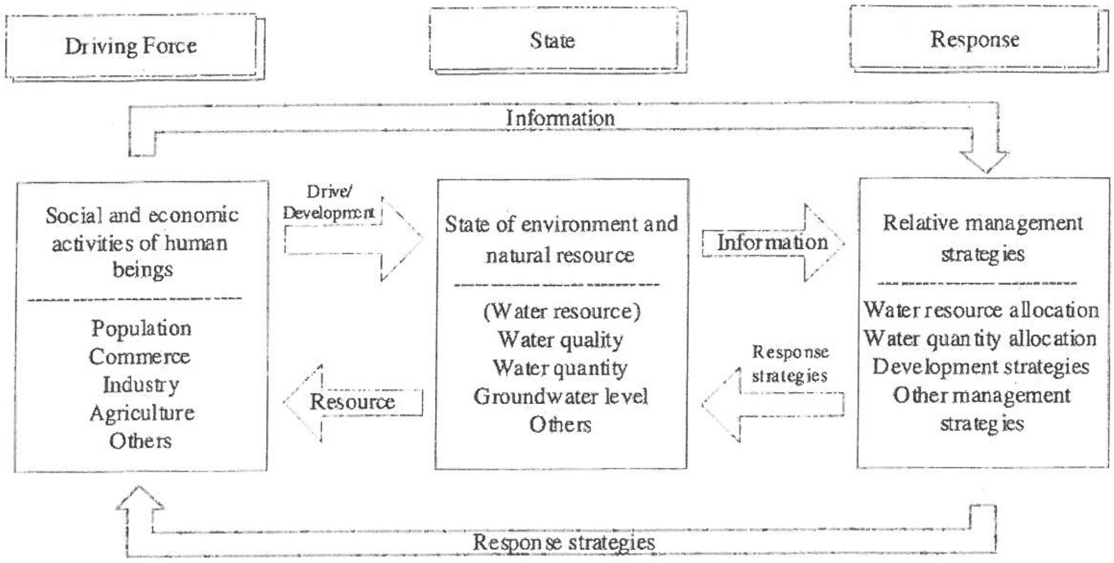

Figure 3 D-S-R analysis system.

and Yunlin counties. In addition, we chose suitable water resource development strategies by these criteria, and according to those suitable strategies and the actual area and condition of water deficiency of each kind of water usage, we focused on industrial water use, human consumption water use, and agricultural water use to set up appropriate water resource development strategies.

2.3. *Selection of groundwater recharge projects*

From several existing and planned projects of storage facilities or detention ponds in Changhua and Yunlin counties, which include the Gukeng artificial lake, Sijhou artificial lake, Dacheng artificial lake, Yunlin artificial lake, the storage facility along the Chomain irrigation system, the artificial lake at the apex of the alluvial fan, the storage facility on the northern bank of the Chou-Shui River floodplain, the storage facility along the Babao tunnel, the storage facility on the southern bank of the Chou-Shui River floodplain, Lunbei artificial lake, Mailiao artificial lake, Tianjhong detention pond, Beigang multi-purpose detention pond, Yiwu multi-purpose detention pond, Ershuei artificial lake, and the dam on the Shia-Shou-Pu reach, we evaluated and selected some appropriate projects which are suitable for groundwater recharge. The storage facilities or detention ponds not only have functions of water source allocation and flood detention but also groundwater recharge. We placed these projects on the selection list and then chosed the most suitable ones through a selection process.

Because these storage facilities or detention ponds were located at different areas and had different objectives, they needed to be selected through several selection procedures to determine the most appropriate groundwater recharge projects. The procedures used in this study are the availability of water source to recharge, the possibility to obtain land, the number of aquifers that infiltration water could flow through, the possibility to raise groundwater level at the end of the Chou-Shui River Alluvial Fan, and the value of infiltration rate of soil. Projects which could pass these procedures were predicted to have a better recharge effect and less resistance to implementation. The selection procedures are shown in Figure 4.

3. Research Results

3.1. *Water resource development projects*

By using the D-S-R analysis system and five criteria, we could select 12 suitable water resource development strategies for Changhua and Yunlin counties (Figure 5) including seawater desalination, artificial storage facility, surplus water source allocation, and groundwater recharge, and so on. Those directions given for the water resource development are predicted to be executed in the study area in the near future.

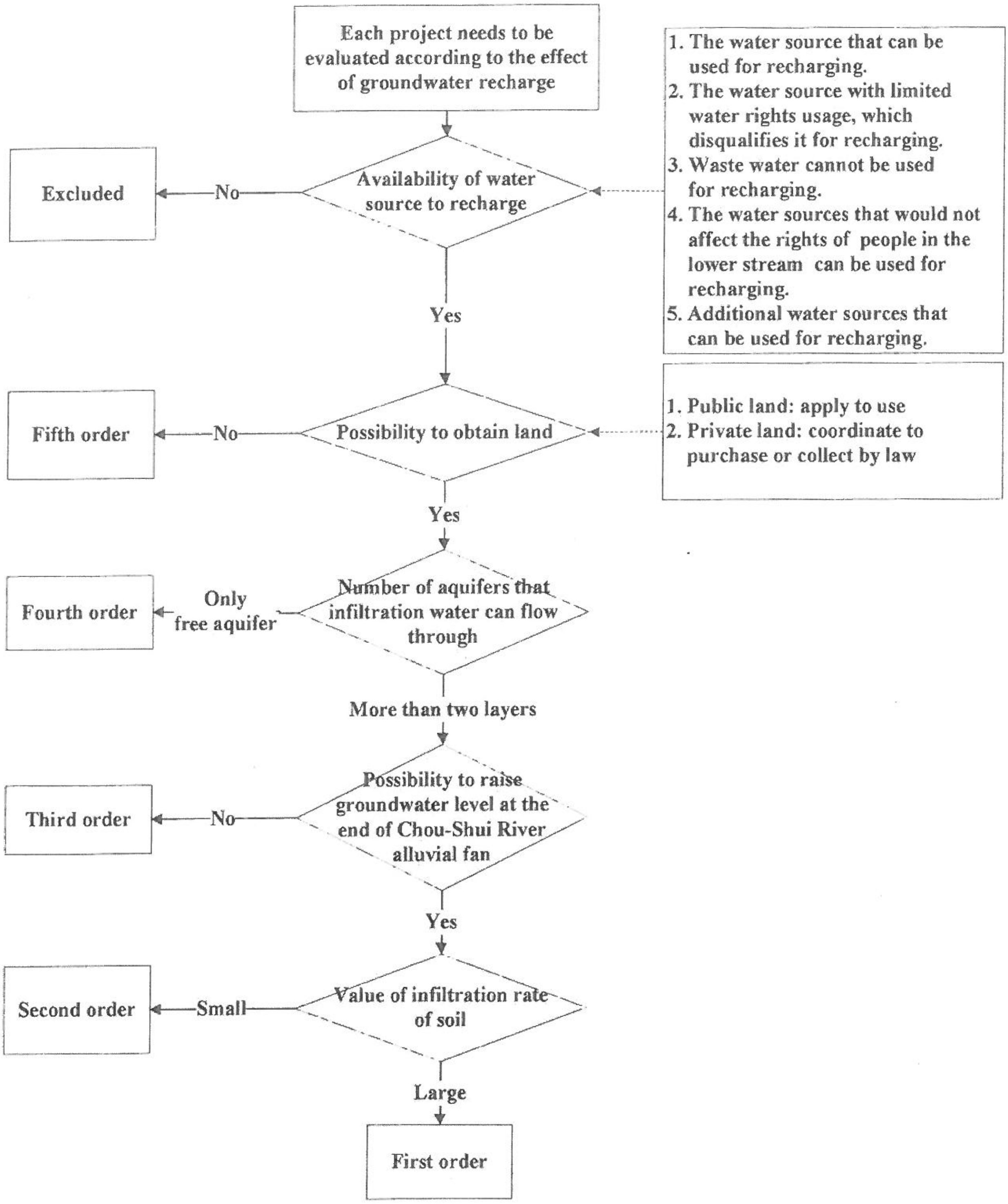

Figure 4 Selection procedures of the groundwater recharge projects.

In addition to those strategies mentioned above, we picked some strategies which could match local characteristics. Regarding Changhua, for example, according to the future land development planning and groundwater pumping condition for agriculture in this area, the situation of overloading industrial and agricultural water usages would still happen. Therefore the water resource development strategies should focus on industrial and agricultural water usages. In the

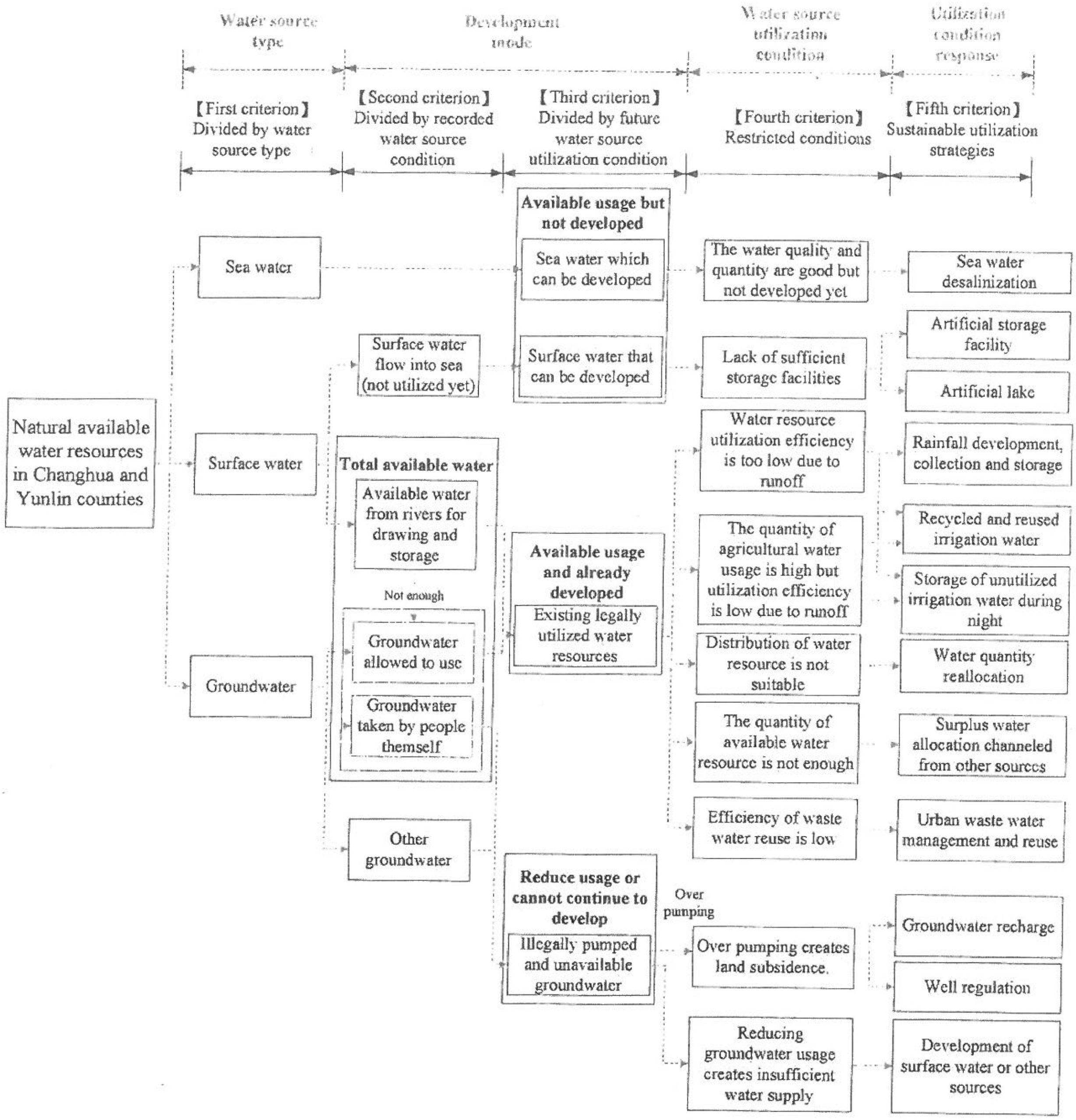

Figure 5 The multi-criteria analysis and strategy study of water resource development in Changhua and Yunlin counties.

aspect of agricultural water use, the irrigation water allocation projects could be the most practical method such as Sijhou artificial lake, Ershuei artificial lake, and the storage facility along Babao tunnel, and so on (Figure 6). Also regarding the aspect of industrial water use, except for the Dadu Weir in Wu River which could supply 0.8 million tons of water per day for industries, the Dacheng artificial lake close to the large-scale industrial parks and sea water desalinization would be the most practical projects because those approaches all grant the industrial parks the advantage of reducing the cost of water delivery.

In Yunlin, because agricultural water use is deficient, in order to raise the agricultural water usage utilization efficiency, we evaluated that the storage and

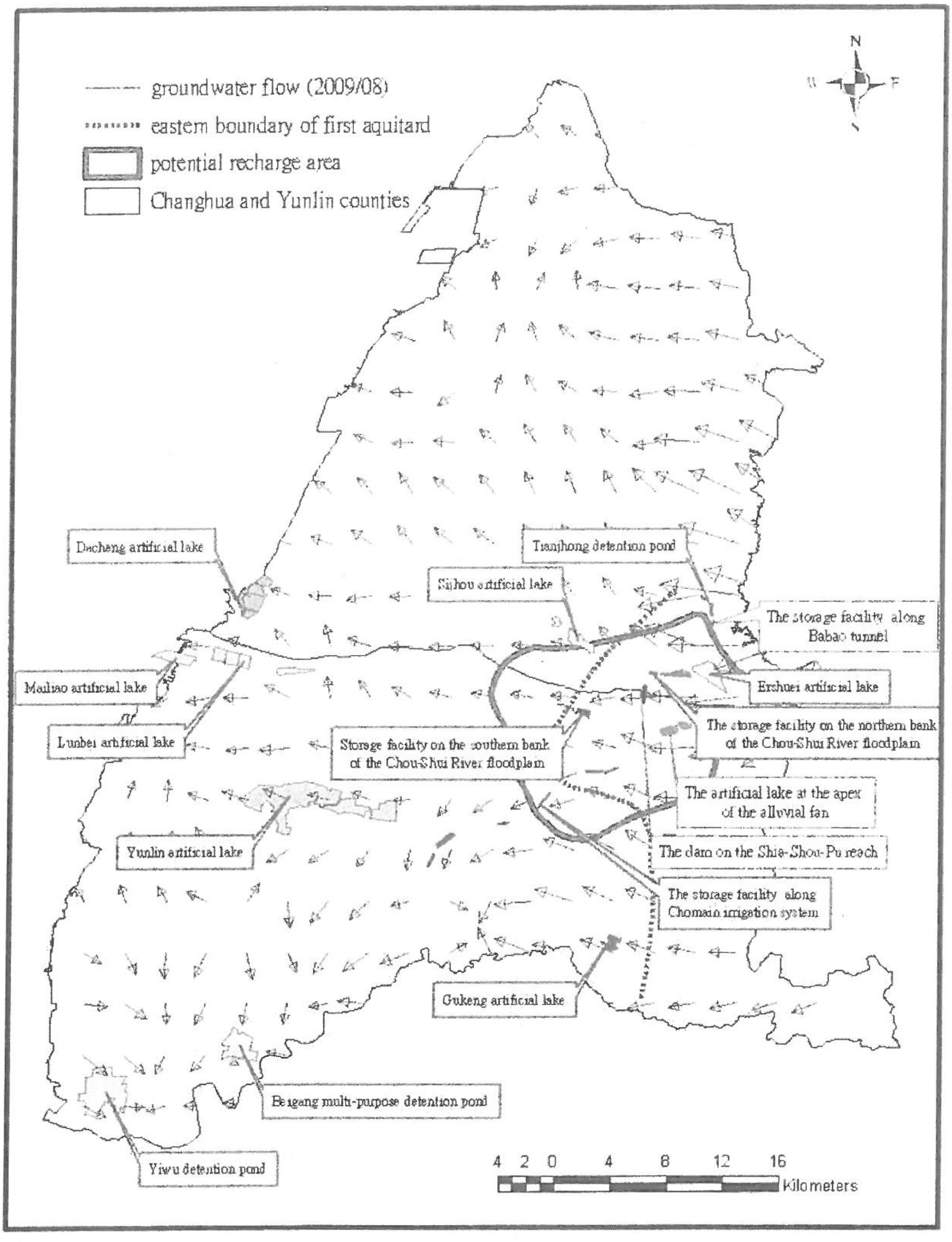

Figure 6 The geological relationship between each project location and selection conditions.

allocation of unutilized irrigation water during night would be the major development strategy which could improve the irrigation runoff problem caused from the irrigation output provided by the Yunlin Irrigation Association. According to the nighttime irrigation water quantity data, the Douliou main tunnel, Chomain irrigation system, and Lu-Chang-Ke tunnel are systems which have a greater potential for development. If the location of these systems are suitable for building large storage facilities to store water, and these systems would be coordinated to operate during the growing seasons with the newly built storage facilities that would store irrigation water during the night (off-peak hours), the surface water utilization efficiency would be better and groundwater pumping would be reduced. On the other hand, the major deficiency areas for industrial water use are located in the divisions of the tapwater supply system of Douliou, Dounan, Huwei, Beigang and Mailiao. Among these water deficiency areas, the Coastal Industrial Park at Mailiao has the highest water demand that will increase in the future. Therefore for the divisions of the tapwater supply system of Mailiao, which is located at the end of a water supply system and is near coastal areas, it is more appropriate to develop sea water desalinization plants to supply industrial water use, and human consumption water use for the areas that have water deficiencies. In addition, for inland areas which are deficient of industrial water use, recycled and reused waste water could be another water resource development strategy.

3.2. *Groundwater recharge projects*

From the method introduced in section 2.2, we selected several groundwater recharge projects. The first selection procedure was to check the availability of water source to recharge. In this procedure, projects with insufficient water such as Mailiao artificial lake, projects which has water rights belonging to Changhua and Yunlin Irrigation Associations such as Yiwu multi-purpose detention pond, Beigang multi-purpose detention pond, Gukeng artificial lake, the storage facility along the Chomain irrigation system, the storage facility along Babao tunnel, Sijhou artificial lake, Ershuei artificial lake, and Tianjhong detention pond, and projects with poor water source quality such as the storage facility on the southern bank of the Chou-Shui River floodplain were excluded.

The second selection procedure was to check the possibility to obtain land. Projects that passed the first procedure and have the possibility of obtaining this land by requesting permission, means of purchase, or collection by law enter the third procedure.

The third selection procedure was to check the number of aquifers that infiltrated water could flow through. Underlying Changhua and Yunlin counties are three aquitards within a large aquifer, creating four layers within the aquifer. The length of the first aquitard extends from the west coast until the boundary line shown on the eastern side in Figure 6. However, those water storage facilities such as Yunlin artificial lake, Lunbei artificial lake and Dacheng artificial lake located on the western coastal area have limited access to only the first layer of the aquifer. On the other hand, projects located on the eastern boundary of the first aquitard such as the artificial lake at the apex of the alluvial fan, the dam on the Shia-Shou-Pu reach, and the storage facility on the northern bank of the floodplain could infiltrate into the second to fourth aquifers. Therefore these projects located on the eastern boundary of the first aquitard could enter the fourth selection procedure.

The fourth selection procedure was to check the possibility to raise groundwater level at the end of the Chou-Shui River Alluvial Fan. According to groundwater flow direction, we evaluated that groundwater below the artificial lake at the apex of the alluvial fan, the dam on the Shia-Shou-Pu reach and the storage facility on the northern bank of the Chou-Shui River floodplain could flow to the end of the Chou-Shui River Alluvial Fan. For this reason, these projects could enter the fifth selection procedure.

The fifth selection procedure was to check the value of the infiltration rate of the soil. We designated the areas that had surface water with infiltration time of less than 200 days, and transmissivity larger than $3000\,m^2/day$ for areas with potential groundwater recharge. By comparing the location of the projects with the areas of potential groundwater recharge, we determined that the artificial lake at the apex of the alluvial fan, the dam on the Shia-Shou-Pu reach, and the storage facility on the northern bank of the Chou-Shui River floodplain would be the first-order projects after going through all of the selection procedures. Figure 6 shows the geological relationship between each project location and selection conditions (boundary of the first aquitard, groundwater flow, and potential groundwater recharge area). Figure 7 shows the selection process.

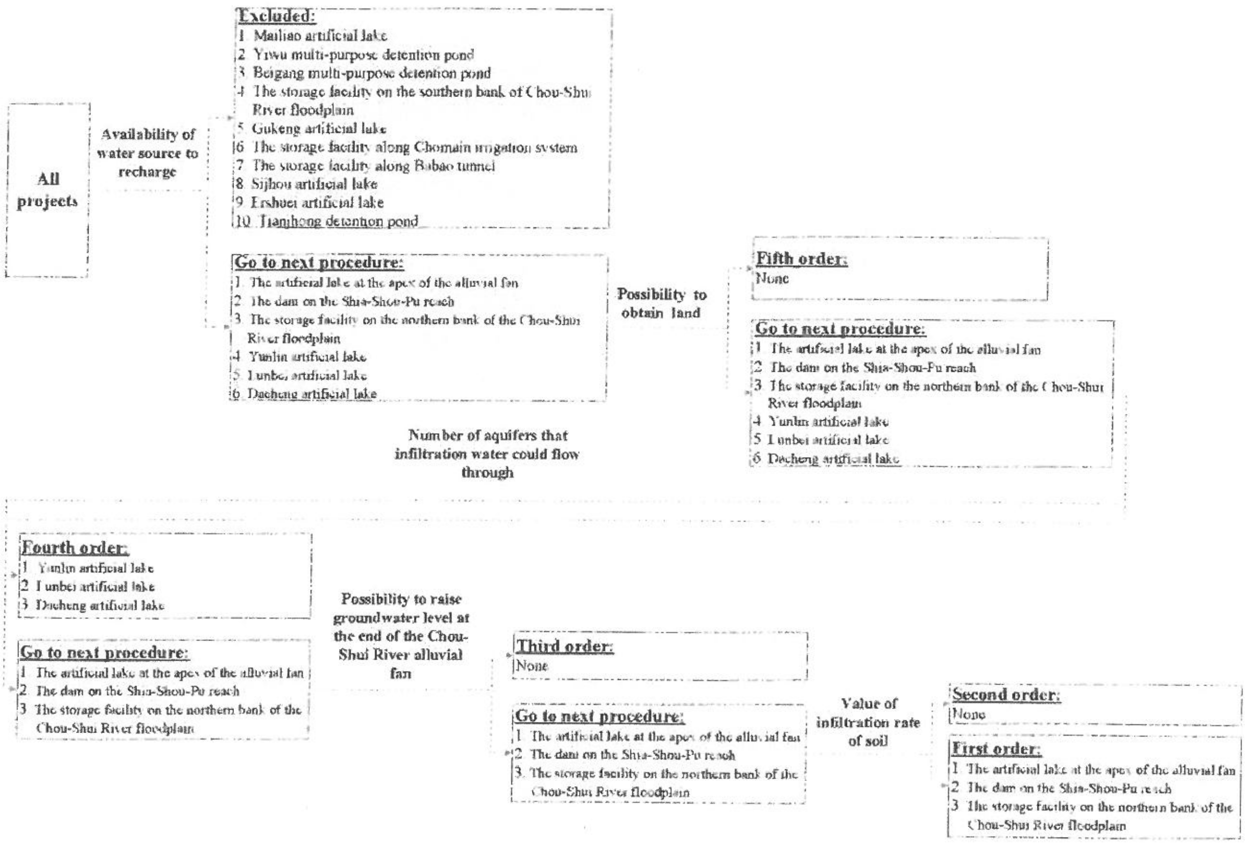

Figure 7 Projects processed through each selection procedure.

4. Conclusion

We used the D-S-R analysis system and selection procedures to choose several methods to prevent continuation of land subsidence. Those methods that belong to the water resource development projects are agricultural water usage allocation, sea water desalinization, and recycled and reused waste water, and methods that belong to the groundwater recharge projects are the artificial lake at the apex of the alluvial fan, the dam on the Shia-Shou-Pu reach and the storage facility on the northern bank of the Chou-Shui River floodplain. We predict that these projects could improve the severe land subsidence problem and conserve the local groundwater. Because both of the D-S-R analysis system and selection procedures are integral analysis methods and are analyzed with a logic framework and consideration for the local characteristics and water resources demands, they can be applied to a smaller or wider region. According to the results of research, Changhau and Yunlin regions now are implementing the project to build the groundwater recharge facility. Besides it also will build the groundwater observation wells to evaluate effectiveness. As a result, the research area will be the demonstration area, and the performance and experiences of this research will be promoted to other land subsidence areas.

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