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Application of Factor Analysis for Characterizing the Relationships between Groundwater Quality and Land Use in Taiwan's Pingtung Plain

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Abstract: Although the average municipal water coverage in Taiwan is quite high, at 93.91%, only around half of the residents in the Pingtung Plain use tap water originating from the Taiwan Water Corporation to meet their needs. This means the exploitation of a substantial amount of groundwater as a source of water to meet drinking, agriculture, aquaculture, and industry requirements. Long-term groundwater quality surveys in Taiwan have revealed obvious contamination of the groundwater in several locations in the Pingtung Plain, with measured concentration levels of some groundwater quality parameters in excess of the permissible levels specified by the Taiwan Environmental Protection Administration. Clearly, establishing a sound plan for groundwater quality protection in this area is imperative for maximizing the protection of human health. The inappropriate use of hazardous chemicals and poor management of land use have allowed pollutants to permeate through unsaturated soil and ultimately reach the underlying shallow unconfined groundwater system. Thus, the quality of the water stored in shallow aquifers has been significantly affected by land use. This study is designed to characterize the relationship between groundwater quality and land use in the Pingtung Plain. This goal is achieved by the application of factor analysis to characterize the measured concentrations of 14 groundwater quality parameters sampled from 46 observation wells, the area percentages for nine land use categories in the neighborhood of these 46 observation wells, and the thicknesses of four unsaturated types of soil based on core samples obtained during the establishment of 46 observation wells. The results show that a four-factor model can explain 56% of the total variance. Factor 1 (seawater salinization), which includes the groundwater quality parameters of EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+, shows a moderate correlation to land used for water conservation. Factor 2 (nitrate pollution), which includes the groundwater quality parameters of NO_3^--N and HCO_3^-, shows a strong correlation to land used for fruit farming and a moderate correlation to the thickness of the gravel comprising unsaturated soil. Factor 3 (arsenic pollution), which is composed of groundwater quality parameters of total organic carbon (TOC) and As, is very weakly affected by land use. Factor 4 (reductive dissolution of Fe^{3+} and Mn^{2+}), which involves Mn^{2+} and Fe^{3+}, is weakly impacted by land use. Based on a geographic visualization of the scores for the four different factors and the patterns for land use, we can demarcate the areas where the groundwater in shallow unconfined aquifers is more vulnerable to being polluted by specific contaminants. We can then prioritize the areas where more intensive monitoring might be required, evaluate current land use practices, and adopt new measures to better prevent or control groundwater pollution.

Keywords: groundwater quality; land use; unsaturated soil; factor analysis; factor score

1. Introduction

Groundwater is a vital and reliable component of water resource supplies around the world. In Taiwan, in areas where there is a shortage of surface water, residents depend upon groundwater to meet their basic daily water demands as well as for irrigation for agriculture and aquaculture. The Pingtung Plain in Southwestern Taiwan is an intensively productive agricultural area, mostly from the cultivation of crops and aquaculture. Approximately 50.5% of the land in the Pingtung Plain is used for agriculture and 5.5% for aquaculture, and agricultural activities have continued to intensify over the last few decades. The total groundwater used annually in the area is 24.3 million tons, with most being used for agriculture (63%), aquaculture (8%), industry and other demands (29%) [1]. Moreover, the residents of the Pingtung Plain are unusual, in that only around 50.8% use municipally supplied tap water even though the average tap water coverage in Taiwan is 93.91%.

Long-term investigations of groundwater quality in Taiwan have revealed obvious groundwater contamination, with the measured concentrations of some groundwater quality parameters at some monitoring wells in the Pingtung Plain in excess of the acceptable levels specified by the Taiwan Environmental Protection Administration [2–5]. The use of contaminated groundwater for drinking, irrigation, aquaculture, and industry can have potentially adverse effects on the health or activities of residents. Exposure to some hazardous chemicals is known to lead to a variety of acute and chronic health effects. For example, arsenic (As) is recognized as a toxicant and carcinogen which can cause Blackfoot disease as well as cancers of the liver, kidney, bladder, prostate, lymphoid tissue, skin, colon, lungs, and nasal cavity, ischemic heart disease, hyperpigmentation, hyperkeratosis, diabetes, and meningioma [6–13]. Arsenic can enter the food chain indirectly—for example, through the consumption of fish cultivated in As-affected groundwater or the ingestion of crops grown using As-contaminated groundwater for irrigation or directly by drinking As-contaminated water [14–16]. Nitrate is a naturally occurring form of nitrogen necessary for crop growth. However, decades of intensive farming in the same area can result in the leaching of excess nitrate from manures and fertilizers into shallow unconfined groundwater system [17–19]. Septic systems and cesspits are also sources of nitrates. All of this makes it one of the most common contaminants in groundwater worldwide. The ingestion of excess nitrate can cause blue baby syndrome, also known as methemoglobinemia, in infants, which can lead to brain damage and sometimes death (e.g., Liu et al. [20]). Both chloride and sodium are highly soluble chemical elements naturally found in groundwater, particularly in coastal areas. However, excess levels of chloride and sodium ions can not only adversely affect the taste of drinking water, rendering it unsuitable for drinking, but high concentrations of chloride and sodium ions in the groundwater can also have an inhibitive effect on the growth of crops. Iron and manganese are metals that occur naturally in soils, rocks, and minerals, but when groundwater comes into contact with these solid materials, they can be dissolved and, with their constituents, released into the water body. If groundwater containing high levels of iron and manganese is used for agriculture or aquaculture, it may inhibit the growth of cultivated crops or farm fish.

Achieving water security and availability for people worldwide is among the principal agenda for the Sustainable Development Goals adopted by all United Nations Member States. To achieve the goal of water security, establishing a sound plan for safe and sustainable groundwater quality management is imperative for protecting human health, ensuring food safety, maintaining access to clean and healthy water resources, and preserving the environment. Although they may be laborious, expensive, time-consuming, and complex, efforts for characterizing groundwater quality are required as a critical step in identifying good and safe water quality. The chemical composition of the groundwater in an aquifer is a direct consequence of the composition of the water that enters the aquifer and the interaction of this groundwater with the surrounding minerals deposited by various natural processes and/or anthropogenic activities. Such effects may significantly modify the various chemical compositions of the groundwater. Groundwater contamination originating from the incidental release of various types of wastes or the inappropriate management of materials used and products generated by industrial, agricultural, and public activities on the land surface is carried along with water infiltration through unsaturated soil, ultimately reaching the water in the underlying aquifer [17]. Groundwater in shallow unconfined aquifers is even more vulnerable to pollution by chemicals derived from anthropogenic activities. Moreover, the close connection between these shallow unconfined aquifers and the overlying land surfaces further supports the premise that groundwater quality is especially affected by land use.

Considering the obvious necessity to protect groundwater sources from contamination through human activities, studies on the relationship between groundwater quality and land use have gained increasing attention over the past couple of decades. One approach is simply to make a comparison between the contaminants in the groundwater and land uses in specific areas. For example, Wang [21] examined the relationship between groundwater quality and land use in Rhode Island in the United States using linear and multiple regression analysis. He found that the areas of residential land use were related to increased levels of chloride and sodium concentrations in well water. Nitrate concentrations were also closely related to increased residential land use. Eckhardt and Stackelberg [22] applied maximum-likelihood logistic regression analysis to investigate the relationship between groundwater quality and land use in Long Island, New York, in the United States. They considered five different study areas and several groundwater quality parameters. Their research results indicated that the presence of nitrate and boron in the groundwater was related to the use of undeveloped forested land. Jeong [23] analyzed the effect of land use and urbanization on groundwater contamination in the Taejon area in South Korea. They grouped groundwater quality parameters on the basis of land usage. Ouyang et al. [24] applied trilinear analysis to estimate the impact of land use on groundwater quality. They considered four different types of land use and five groundwater quality parameters. Their results demonstrated that nitrate and nitrite (NOx) were related to the presence of septic tanks and that total organic nitrogen (TON) was the dominant species in the groundwater beneath forested lands. Penha [25] investigated the effect of land use on groundwater quality in Southern Portugal by performing a comparison of 12 groundwater quality parameters and five major land uses. Groundwater beneath olive groves had high levels of electrical conductivity, calcium, potassium, sulfate, and phosphate. Dry crop land was correlated with the presence of calcium, magnesium, chloride, electrical conductivity, phosphate, and sulfate. Vineyard land was strongly correlated with high sulfate and phosphate levels.

The aforementioned studies deliver invaluable insights into the relationships between groundwater quality and land use. It should also be noted that the impact of land use on groundwater quality may also be significantly affected by the characteristics of unsaturated soil located between the land surface and the water table of a shallow unconfined aquifer. However, the existing studies on this topic are relatively sparse and even fewer include the factor of the material properties of the unsaturated soil in their investigations. The material properties of unsaturated soil will play an important role in determining aquifer vulnerability. Thus, this study aims to characterize the relationships between groundwater quality and land use in the Pingtung Plain by considering the material properties of the unsaturated soil. The study combines the data regarding groundwater quality parameters, land use patterns, and material properties of unsaturated soil. The factor analysis method is used to analyze the measured concentrations of 14 different water quality parameters for groundwater samples from 46 observation wells, the area percentages for nine different land use categories in the neighborhood of the 46 observation wells, and the thickness of four different types of unsaturated soil based on the core samples obtained during the establishment of the 46 observation wells. Specifically, the scores for the factors are mapped to demarcate the areas that are more vulnerable to land use contamination, prioritize the areas where more intensive monitoring of groundwater quality might be needed, evaluate current land use practices, and adopt new measures to better prevent or control potential sources of pollution.

2. Materials and Methods

2.1. Study Area

The Pingtung Plain lies in the southeast part of Taiwan and covers most of Pingtung County and a small part of Southeastern Kaohsiung City, as depicted in Figure 1. The plain is bound by the Taiwan Strait on the south, the foothills of the Central Mountain Range and river valleys on the north, the Fengshan Fault on the west, and the Chaozhou Fault on the east. It has a total area of 1270 km^2, is approximately 60 km long from north to south and 20 km wide from west to east, and is divided into 30 townships. The total population is more than 870,000 persons distributed nonuniformly throughout the area. The Kaoping River is the largest river crossing the plain, flowing from the Central Mountain Range to the Taiwan Strait, with other shorter rivers such as the Tungkang River, Linbian River, and Shihwen River also passing through the plain. According to climate statistics for the period between 2010 and 2018, the Pingtung Plain receives an average annual precipitation ranging from 1160 to 3675 mm, with an average of 2428 mm. Most of the precipitation is concentrated between May and September.

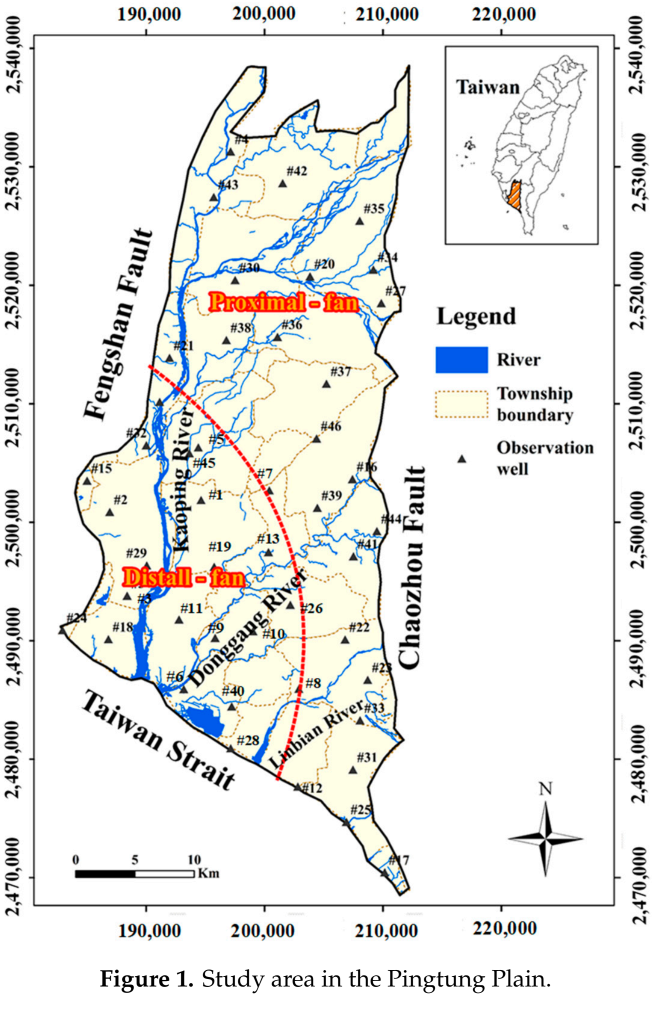

Figure 1. Study area in the Pingtung Plain.

Drilling and sequence stratigraphic studies for characterizing the subsurface geology and hydrogeology within a subsurface depth of 250 m were conducted from 1995 to 1998 during the "Integrated Taiwan Groundwater Monitoring Network Project". Fifty hydrogeological investigation stations and 126 monitoring wells were established by the Water Resource Agency (WRA) [26]. The hydrogeological investigation stations each included one or more wells with screening at different depths for observation of groundwater levels and the monitoring of groundwater quality in the different aquifers. The results of these drilling and sequence stratigraphic studies demonstrated that the geology underlying the plain is comprised of unconsolidated Late Pleistocene and Holocene age sediments and contains abundant groundwater. Most of the sediments consist of coastal and estuarine sand and mud, with abundant shallow marine and lagoon shells and foraminifers. The plain can be partitioned into proximal-fan and distal-fan areas. The deposits in the distal fan area can be further classified into eight overlapping sequences, including four marine sequences and four non-marine sequences. The non-marine sequences are composed of highly permeable coarse sediments and are thus classified as "aquifers", while the marine sequences which contain less permeable fine sediments are regarded as "aquitards". It should be noted that the aquitards are found mainly in the distal-fan area rather than in the proximal-fan area. Figure 2 shows the hydrogeological profile of the study area from west to east. There are four usable aquifers, labeled Aquifer 1, Aquifer 2, Aquifer 3, and Aquifer 4, from top to bottom, at depths of 0–70, 40–130, 90–180, and 160–250 m, respectively. The principal source of groundwater in the plain is from the infiltration of natural rainwater, which collects in the principal, ancient Quaternary reservoir. The proximal-fan area and the river valleys on the eastern and northern boundaries are the major regions for aquifer recharging. Groundwater flows from these regions to the western coastal area bordering the Taiwan Strait.

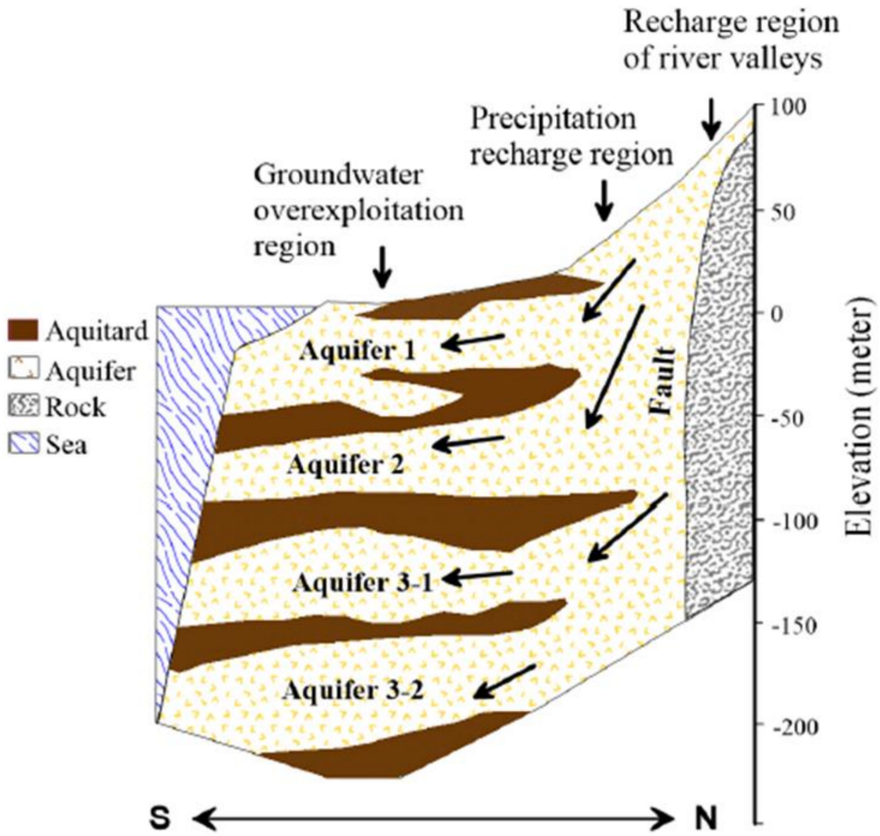

Figure 2. Hydrogeological profile of the Pingtung Plain.

The land use patterns depicted in Figure 3 are based on information obtained from the Land Use Investigation of Taiwan by the National Land Survey and Mapping Center of the Ministry of Interior, Taiwan. Approximately 50.5% of the area is used for agriculture and 5.5% for fishponds. During dry months or years, large amounts of groundwater are extracted to meet the water resource requirements for farmlands, fishponds, and households. This has led to an increase in the salinity of the groundwater, a reduction in the pollution diluting capability of the surface water, and an increase in the occurrence of severe land subsidence and seawater intrusion.

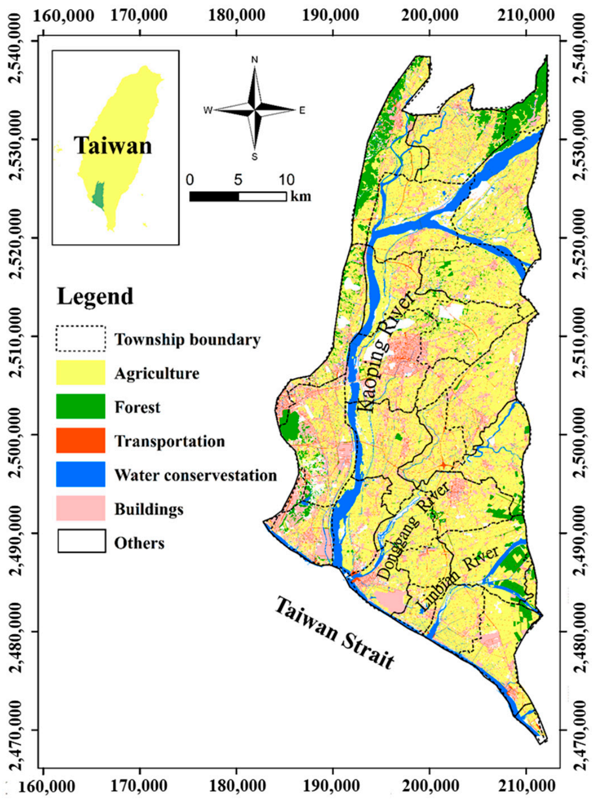

Figure 3. Map of land use in the Pingtung Plain.

2.2. Data Collection and Processing

Three types of data including groundwater quality parameters, land use categories, and material types of unsaturated soil are required to characterize the relationships between groundwater quality and land use. The data matrices of concentrations for 14 groundwater quality parameters, area percentages for 9 different land use categories, and thickness for 4 different material types of unsaturated soil are provided in Tables A1–A3 in Appendix A. After the "Integrated Groundwater Monitoring Network Project", long-term surveys of the groundwater quality in established groundwater observation wells have continued to be conducted by the Agricultural Engineering Research Center (AERC), with financial support from the Taiwan Water Resource Agency. The measurement data for the groundwater quality parameters considered in this study are mainly obtained from the annual reports published by the Water Resources Agency from 2014 to 2019. Only groundwater quality for Aquifer 1 (a shallow unconfined aquifer) is considered. We look at 14 groundwater quality parameters including electrical conductivity (EC), *Escherichia coli* (E. Coli), Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, NO_3^--N, HCO_3^-, TOC, As, Fe^{3+}, and Mn^{2+} from 46 observation wells in the Pingtung Plain established by the Taiwan Water Resource Agency.

Data for land use are obtained from the Land Use Investigation of Taiwan by the National Land Survey and Mapping Center of the Ministry of Interior, Taiwan. Because the data for land use patterns are categorical rather than numerical, they must be converted to facilitate the execution of factor analysis. The area percentages for different land use categories in the vicinity of the well have been used in several studies to facilitate the characterization of the relationship between land use and groundwater quality [27]. However, selection of the size of the area surrounding a well for calculating the area percentages of different land use categories is subjective. Wang [21] argued that a circular area around a well with a radius of 1000 ft was optimal to evaluate the relationship between groundwater quality and land use. Herein, we consider 9 land use categories including rice field, dryland, fruit farm, uncultivated land, aquaculture, livestock, forest, water conservation, and human settlement. Table A2 summarizes the area percentages for the 9 land use categories in the vicinity of the 46 observation wells.

The type of geological material in unsaturated soil is often the main factor controlling the vertical movement of pollutants from the land surface as they seep into shallow unconfined aquifers. The thickness of the different types of geological material can be used to calculate the permeability of such unsaturated soil. The thicknesses of the various types of unsaturated soil are calculated from borehole data from observation wells that have been published by the Taiwan Central Geological Survey [28]. The soil types are classified into four groups including gravel, coarse sand, fine sand, and clay, corresponding to grain sizes of >2.0, 0.25–2.0, 0.063–0.25, and <0.063 mm, respectively.

2.3. Factor Analysis

Factor analysis (FA) is a multivariate statistical approach that is extensively used to describe the general relationships between several observed variables in terms of a potentially lower number of unobserved variables, which are called factors, with minimum loss of the original information. The values of the different variables should be standardized and normalized prior to FA to avoid the problem of "no commensurate units". The mean and standard deviation of the standardized variables are thus zero and unity, respectively. All variables are standardized by applying the following transformation:

$$Z_{i,j} = \frac{X_{i,j} - \overline{X_i}}{S_i} \quad (1)$$

where $Z_{i,j}$ are the *j*th values of the *i*th standardized variables; $X_{i,j}$ are the *j*th observations of the *i*th variables, $\overline{X}_i$ is the mean of the *i*th variable; S_i is the standard deviation of the *i*th variable.

In this study, factor analysis is performed by using the principal component analysis (PCA) method. The procedure for FA is as follows. The correlation matrix, i.e., the array of correlation coefficients for all possible pairs of all standardized variables, is calculated. After the calculation of the correlation matrix, the appropriateness of the factor model is evaluated. The Kaiser–Meyer–Olkin (KMO) index is computed to measure the sampling adequacy that indicates the proportion of variance that is common variance, i.e., that which might be caused by underlying factors. A higher value generally indicates that FA analysis may be suitable. When the KMO value is greater than 0.5 and the significance (*p* value) is smaller than 0.001, it indicates that the data are suitable for FA. Subsequently, the eigenvalues and their corresponding eigenvectors (principal components) as well as the variance for the correlation matrix are obtained. The sequence of the factors corresponding to the magnitudes of the eigenvalues is defined. The values of the eigenvalues and variances associated with each individual factor are summed up to be expressed as a cumulative eigenvalue and percentage of variance, respectively. Although the factor matrix obtained in the extracted phase is indicative of the relationship between the factors and the individual variables, it is usually difficult to identify meaningful factors. Therefore, a process for rotation of the factor axis is commonly executed to yield a structure where the factors are clearly marked by high loadings for some variables and low loadings for others, thus facilitating the identification of meaningful factors. In this study, Kaiser's varimax rotation scheme is employed [29].

3. Results and Discussion

This study applies FA to characterize the relationship between the groundwater quality and land use, combining the measured concentrations for 14 groundwater quality parameters sampled from 46 observation wells belonging to the Taiwan WRA, the area percentages for nine land use categories in the vicinity of these 46 observation wells, and the thicknesses of four types of unsaturated soil according to the core samples obtained during the establishment of the 46 observation wells. Prior to investigation of the relationship between groundwater quality and land use by FA, a descriptive statistical analysis of all the collected data is routinely executed. Table 1 shows the descriptive statistics for the 14 groundwater quality parameters, area percentages for the nine land use patterns, and the thicknesses of the four types of unsaturated soil. As can be seen in Table 1, there is moderate to low variability (standard deviation) for the majority of the variables.

Table 1. Descriptive statistics for 14 groundwater quality parameters, percentages of areas for 9 land use patterns and thicknesses of 4 unsaturated soil types from 46 observation wells in the Pingtung Plain.

Parameter	Average (mg/L)	Maximum (mg/L)	Minimum (mg/L)	Standard Deviation (-)	Coefficient of Variation (-)	Exceed the Standard for Drinking	Percentage, %	Exceed the Standard for Agriculture	Percentage, %	Exceed the Standard for Aquaculture	Percentage, %
EC	3155.60	35,541.13	251.00	7486.01	2.4	–	–	13	28	–	–
HCO_3^-	170.89	340.89	19.30	77.46	0.5	9	–	–	–	–	–
E. Coli	503.07	9345.00	2.50	1608.82	3.2	15	33	–	–	0	0
Cl^-	1075.45	16,562.50	1.85	3945.15	3.7	4	9	4	9	–	–
SO_4^{2-}	185.86	2104.43	1.03	467.96	2.5	3	7	3	7	–	–
NO_3^--N	1.86	9.38	0.01	2.47	1.3	0	0	–	–	–	–
TOC	0.44	3.35	0.08	0.48	1.1	0	0	–	–	–	–
As	0.02	0.29	0.00	0.05	2.6	12	26	4	9	4	9
Fe^{3+}	4.08	114.34	0.01	16.77	4.1	29	63	3	7	–	–
Mn^{2+}	0.37	2.62	0.00	0.60	1.6	29	63	20	44	–	–
Ca^{2+}	88.51	304.00	9.30	63.23	0.7	–	–	–	–	–	–
Mg^{2+}	74.97	1002.50	4.86	223.61	3.0	–	–	–	–	–	–
Na^+	488.15	7947.50	6.12	1778.95	3.6	–	–	–	–	–	–
K+	22.13	318.63	0.76	68.91	3.1	–	–	–	–	–	–
Rice field	4.52	40.68	0.00	9.47	2.09						
Dryland	12.26	61.56	0.00	17.21	1.40						
Fruit farm	30.21	99.33	0.00	31.40	1.04						
Uncultivated land	0.51	5.18	0.00	1.21	2.36						
Aquaculture	6.70	63.39	0.00	12.94	1.93						
Livestock	2.39	15.66	0.00	4.22	1.77						
Forest	2.62	24.94	0.00	5.57	2.12						
Water conservation	7.25	76.96	0.00	16.30	2.25						
Human Settlement	20.47	78.96	0.00	21.49	1.05						
Gravel	14.44	64.74	0.00	19.07	1.32						
Coarse sand	4.22	34.34	0.00	6.60	1.56						
Fine sand	2.26	13.52	0.00	3.05	1.35						
Clay	4.09	22.54	0.00	5.85	1.43						

The highest variabilities in the measured concentrations are obtained for the following groundwater quality parameters: E. Coli, Fe^{3+}, Cl^-, Na^+, EC, K^+, Mg^{2+}, As, $SO_4{}^{2-}$, Mn^{2+}, $NO_3{}^-$-N, and TOC, with the coefficient of variation being above 1.0, followed by Ca^{2+} and $HCO_3{}^-$. Land use for water conservation and uncultivated land show the greatest variability of area percentages for land use patterns. The largest variability shown for thickness of unsaturated soil type is for coarse sand.

Before performing factor analysis, KMO and Bartlett's test of sphericity are conducted to examine whether the data are suitable for FA. The computing software package IBM SPSS Statistics Version 22 (IBM Corp., Armonk, NY) is used to perform FA. A KMO value of 0.618 and p value of much less than 0.001 calculated in this study indicate that the data are suitable for FA. Then, the correlation matrix for all standardized variables is calculated, as shown in Table A4.

Table 2 lists the eigenvalues, percentage of variances, cumulative eigenvalues, and cumulative percentage of variances associated with the first six factors. It can be seen that the first six factors account for 67% of the total variance of 27 variables.

Table 2. The factor loading of varimax rotation.

Common Factor	Eigenvalues	Percentages of Variance,%	Cumulative Eigenvalues,%
1	7.42	28	28
2	3.36	12	40
3	2.50	9	49
4	1.83	7	56
5	1.55	6	62
6	1.38	5	67

Table 3 summarizes the individual factor loadings from the varimax rotation factor matrix for a four-factor model. Following Liu et al. [30], the terms "weak", "moderate", and "strong" are defined as corresponding to absolute loading values of <0.4, 0.4~0.6, and >0.6, respectively.

Table 3. The factor loading of varimax rotation.

Parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Water quality						
EC	**0.945**	0.022	−0.005	−0.046	−0.029	0.007
$HCO_3{}^-$	0.074	**0.667**	0.294	0.137	0.101	−0.147
E. Coli	−0.095	−0.003	−0.020	0.099	0.147	−0.041
Cl^-	**0.986**	0.031	0.000	0.041	−0.052	−0.058
$SO_4{}^{2-}$	**0.983**	0.053	−0.032	0.004	−0.034	−0.049
$NO_3{}^-$-N	−0.153	**−0.669**	−0.212	−0.122	0.223	0.017
TOC	−0.079	0.213	**0.947**	0.050	0.050	0.019
As	−0.027	0.168	**0.923**	−0.053	−0.041	−0.104
Fe^{3+}	−0.076	0.161	0.015	**0.858**	−0.076	−0.098
Mn^{2+}	0.244	0.089	−0.020	**0.833**	0.064	0.101
Ca^{2+}	**0.838**	0.304	−0.117	0.054	0.146	−0.012
Mg^{2+}	**0.989**	0.030	0.008	0.051	−0.038	−0.053
Na^+	**0.989**	0.024	0.005	0.043	−0.042	−0.053
K^+	**0.985**	0.034	0.086	0.050	−0.024	−0.041
Land use						
Rice field	−0.146	0.341	0.017	−0.106	**0.612**	−0.219
Dryland	−0.220	0.389	−0.015	0.372	0.013	−0.180
Fruit farm	−0.250	**−0.742**	−0.148	−0.090	−0.135	−0.039

Table 3. *Cont.*

Parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Uncultivated land	−0.067	−0.077	−0.123	−0.066	0.044	**0.803**
Aquaculture	0.312	0.146	0.322	−0.154	0.467	−0.077
Livestock	−0.113	−0.162	−0.054	0.084	**0.837**	0.033
Forest	−0.126	0.006	−0.111	0.171	−0.138	0.012
Water conservation	**0.415**	0.094	0.061	0.051	−0.123	−0.050
Human settlement	−0.186	**0.494**	−0.167	0.033	−0.240	0.495
Geological material						
Gravel	−0.176	**−0.494**	−0.289	−0.249	−0.123	−0.177
Coarse sand	−0.217	−0.002	−0.196	−0.085	0.085	−0.029
Fine sand	−0.072	0.287	−0.213	−0.191	−0.239	0.017
Clay	−0.140	−0.012	0.061	0.045	−0.144	**0.724**

Factor 1 explains 28% of the total variance and shows strong positive absolute loading values for EC, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+ and a moderate positive absolute loading value for land used for water conservation. Liu et al. [30] applied FA to assess the groundwater quality in areas of Taiwan with Blackfoot disease. They identified this type of factor as duo to "the seawater salinization" because of the presence of EC, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, and K^+, which are indicative of the effects of seawater intrusion on groundwater quality. Figure 4 shows a geographic visualization of the scores for factor 1. High scores are found for observation wells in the townships of Sinyuan, Donggang, Linbian, and Fangliao, which are situated in coastal regions. Figure 5 depicts a geographic visualization of EC concentration of land used for water conservation.

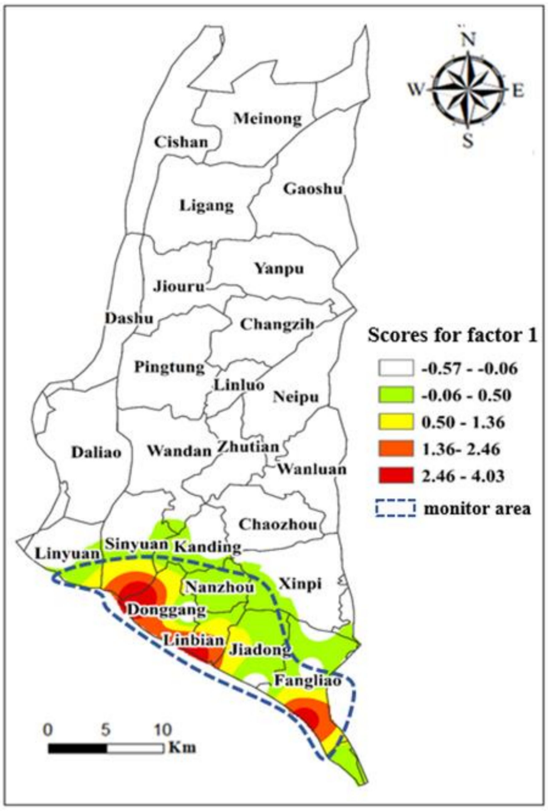

Figure 4. Geographical visualization of factor scores for factor 1, the red area (high score) represent high seawater salinization in the coast.

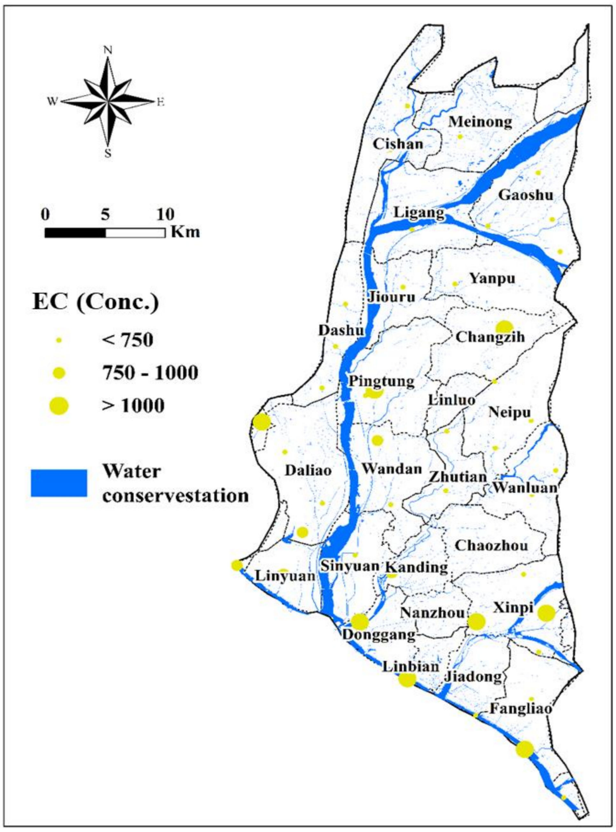

Figure 5. Spatial distribution of the EC and water conservation.

Factor 2 explains 12% of the total variance, with a strong positive absolute loading value for HCO_3^-, a strong negative loading values for NO_3^--N, strong negative absolute loading values for land used for fruit farming, moderate positive absolute loading values for human settlement, and moderate negative loading values for gravel. Figure 6 shows a geographic visualization of the scores for factor 2. High negative absolute scores are found for observation wells in townships of Gaoshu, Yanpu, Changzih, Neipu, and Wanluan near the Central Mountain Range. Figure 7 shows a geographic visualization of HCO_3^- and NO_3^--N concentration, land used for fruit farming, and the thickness of the gravel. It can be seen that land used for growing fruit has high NO_3^--N and low HCO_3^- concentrations. Jang and Chen [31] reported that the NO_3^--N concentration was highly correlated with land use for fruit farming. This result is also similar to those documented by Chen and Liu [32], who explained that the thick layer of gravel present in the proximal part of the Choushui River alluvial fan allows NO_3^--N to quickly move downward to deep aquifers (more than 200 m down). This factor is related to "nitrate pollution".

Factor 3 explains 9% of the total variance, with strong positive loading values for TOC and As. This close correlation between TOC and As was also reported by Liu et al. [30]. They explained that TOC is the major factor controlling the liberation of As. They found that As was adsorbed by the TOC near the redox boundary during oxidation and then liberated by the TOC by reductive dissolution/desorption or by ion exchange with seawater. The very low correlation between As and any land use patterns can be considered a direct consequence of the fact that As is a naturally occurring chemical contaminant. Figure 8 shows a geographic visualization of the scores for factor 3. High absolute score values are found at observation wells in the townships of Donggang, Linbian, Jiadong, and Nanzhou, which are located in the southwestern coastal regions. Figure 9 depicts the spatial distribution of As and TOC. Following Liu et al. [30], factor 3 is related to "arsenic pollution".

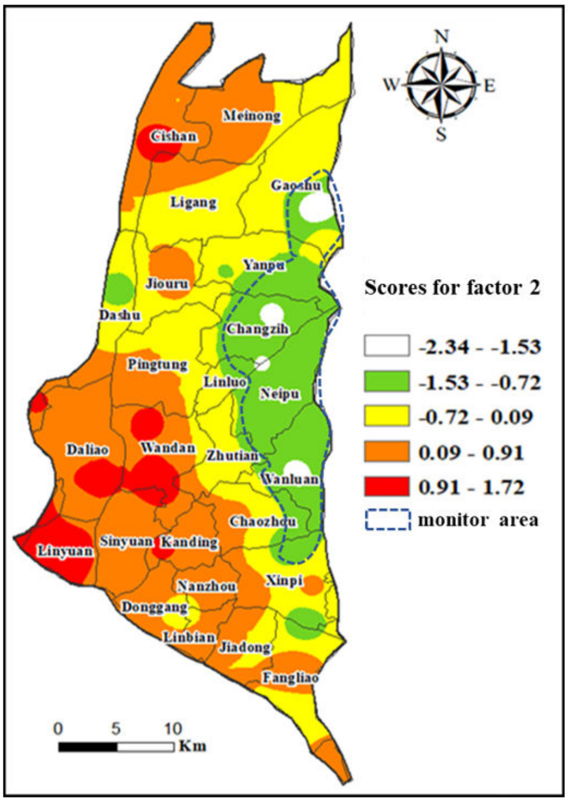

Figure 6. Geographical visualization of factor score for factor 2, the green and white area (low score) represent high nitrate pollution.

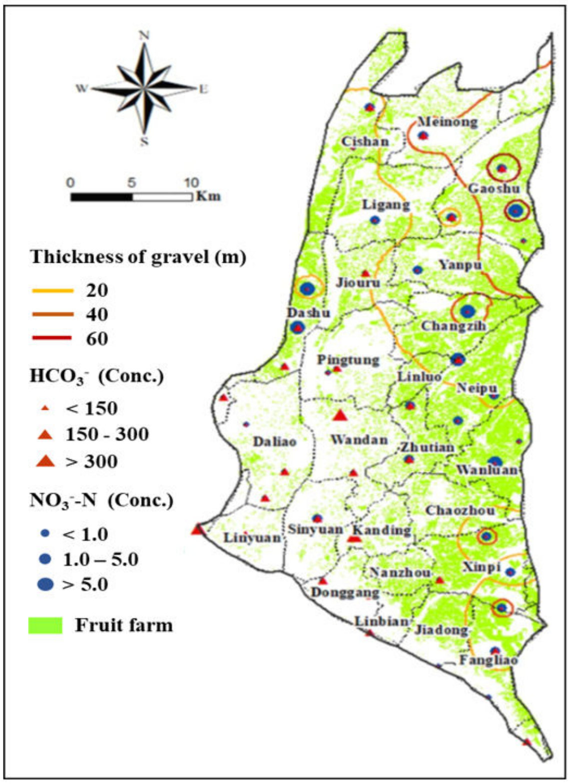

Figure 7. Spatial distribution of the NO_3^--N, HCO3-, fruit farm, and thickness of gravel.

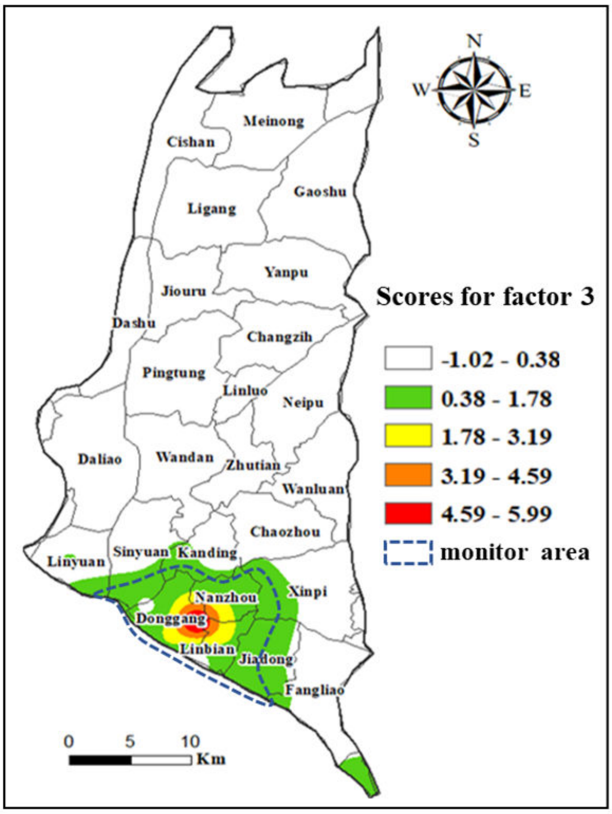

Figure 8. Geographical visualization of factor score for factor 3, the red area (high score) represent high arsenic pollution.

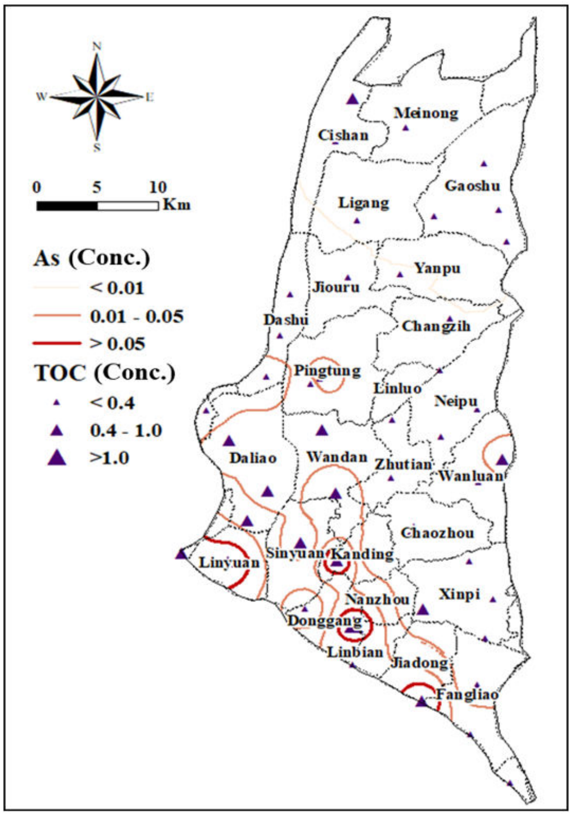

Figure 9. Spatial distribution of As and TOC.

Factor 4 explains 7% of the total variance, with strong positive absolute loading values for Mn^{2+} and Fe^{3+}. The positive correlation between Mn^{2+} and Fe^{3+} can be explained by the fact that they are both derived from the reductive release of a mineral which typically exists in groundwater. Figure 10 shows a geographic visualization of the scores for factor 4. High positive absolute score values are found at observation wells in the townships of Daliao, Linyuan, which are located in the southwestern coastal regions. Figure 11 depicts a geographic visualization of Mn^{2+} and Fe^{3+}. This factor is related to reductive dissolution of Fe^{3+} and Mn^{2+}, because the presence of Mn^{2+} and Fe^{3+} in the groundwater is a direct result of the reductive dissolution.

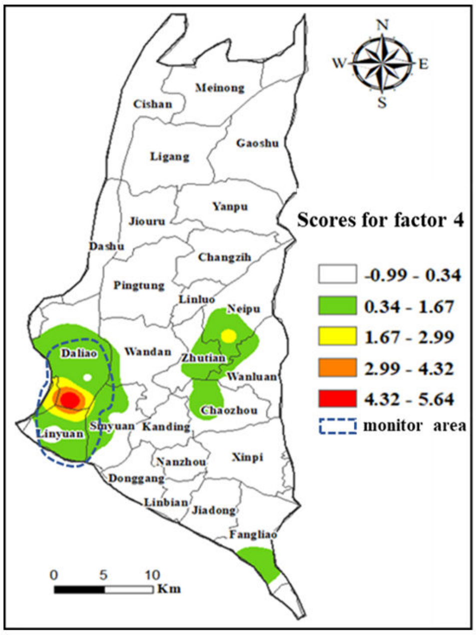

Figure 10. Geographical visualization of factor score for factor 4, the red area (high score) represent high reductive dissolution of Fe^{3+} and Mn^{2+} in this area.

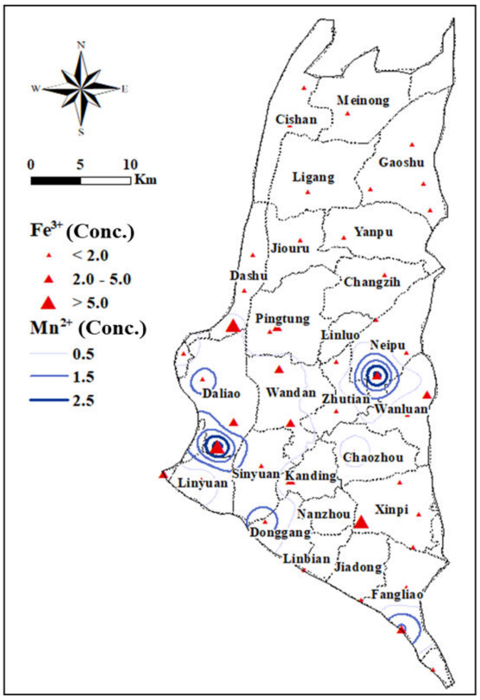

Figure 11. Spatial distribution of $Mn^{2+}$and Fe^{3+}.

Factors 5 and 6 show very low absolute loading values for all groundwater quality parameters and so are not discussed here.

4. Conclusions

In this study, factor analysis is applied to identify the relationship between groundwater quality and land use. The results show that a four-factor model can explain 56% of the total variance. Factor 1 (seawater salinization), which includes the groundwater quality parameters for EC, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, and K^+ is moderately correlated to land used for water conservation. Factor 2 (nitrate pollution), which includes the groundwater quality parameters for NO_3^--N and HCO_3^-, shows a close correlation to land used for fruit farming and the thickness of the gravel in the unsaturated soil. Factor 3 (arsenic pollution), which includes the groundwater quality parameters for TOC and As, is very weakly affected by land use patterns. Factor 4 (reductive dissolution of Mn^{2+} and Fe^{3+}), which is related to the concentration of Mn^{2+} and Fe^{3+}, is also weakly impacted by land use patterns. For a sound plan for safe and sustainable groundwater quality management, identification of the source of contamination is the first priority. The NO_3^--N concentration closely correlated with land use for fruit farming and the thickness of the gravel in the unsaturated soil clearly identifies the that fruit farming is the major NO_3^--N source, and the thick layer of gravel present in the townships of Gaoshu, Yanpu, Changzih, Neipu, and Wanluan near the Central Mountain Range allows NO_3^--N to quickly move downward to deep aquifers. Following the identification of the NO_3^--N source, pollution control for these NO_3^--N contaminated regions could include public education to raise awareness of the use of fertilizer for fruit farming or change the land use for fruit farming.

Author Contributions: C.-P.L. and J.-S.C. conceived the study and its design, C.-H.W. performed the data analysis, T.-W.C. provided the data resources, C.-P.L., S.-W.W., T.-W.C. and J.-S.C. interpreted the results, C.-P.L. wrote the manuscript, S.-W.W. and J.-S.C. made a critical revision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Tables A1–A3 give the data matrices of concentrations for 14 groundwater quality parameters, area percentages for 9 different land use categories and thickness for 4 different material types of unsaturated soil. Table A4 give the matrix of correlation coefficients for all variables.

Table A1. Data matrix for concentrations for 14 water quality parameters.

Wells	E.C. (μ S/cm)	HCO_3^- (mg/L)	E. Coli (CFU/100mL)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^--N (mg/L)	TOC (mg/L)	As (mg/L)	Fe^{3+} (mg/L)	Mn^{2+} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)
#1	993	314.0	4	50.5	159	0.048	0.55	0.008	4.305	0.600	151.000	22.975	34.275	4.503
#2	542	139.0	70	27.7	59.5	0.005	0.50	0.004	0.474	1.160	45.600	22.700	35.550	3.120
#3	752	274.8	100	109.5	1.033	0.122	0.72	0.017	114.335	2.619	78.433	37.133	73.467	15.908
#4	700	213.5	63	17.5	69.4	1.905	0.60	0.001	0.025	0.373	104.250	22.800	21.150	15.650
#5	10,385	217.0	3	16.6	58.05	0.005	0.35	0.010	3.080	0.408	115.000	13.600	18.450	7.465
#6	35,541	262.4	14	16,562.5	1971.25	0.026	0.30	0.008	0.977	1.311	304.000	1002.500	7947.500	318.625
#7	498	165.0	238	18.3	107	1.310	0.35	0.001	0.102	0.106	105.000	15.650	12.900	1.800
#8	4700	195.5	198	19.0	40.1	0.005	0.95	0.009	6.140	0.450	76.800	22.050	22.400	4.350
#9	780	307.7	9	31.6	102.843	0.604	0.67	0.068	4.929	0.246	122.571	24.257	75.243	2.490
#10	411	81.0	3	3.9	28.75	1.005	0.50	0.001	3.685	0.291	34.550	8.340	19.600	1.385
#11	634	215.0	275	84.9	59.35	2.815	0.50	0.001	0.403	0.826	118.000	21.500	39.400	19.800
#12	453	133.5	205	79.6	10.95	0.005	0.80	0.076	0.565	0.137	48.250	18.200	46.700	2.930
#13	515	175.0	9,345	17.0	72.933	3.190	0.40	0.004	0.903	0.167	82.067	14.867	14.233	1.513
#14	405	154.0	50	18.9	51.55	5.740	0.25	0.000	0.181	0.194	59.750	20.300	23.600	4.660
#15	3036	184.5	75	28.0	10.35	0.005	0.35	0.010	0.882	0.306	45.800	8.015	65.900	1.970
#16	436	19.3	28	5.3	35.25	2.615	0.15	0.003	0.431	0.029	9.295	7.350	12.850	1.091
#17	629	171.0	13	72.1	36.25	0.105	0.40	0.043	1.530	0.107	84.250	16.700	46.700	1.535
#18	869	340.9	23	1178.4	108.4	0.256	0.61	0.063	4.821	0.122	111.000	30.800	45.222	6.772
#19	494	177.0	600	25.0	103.8	0.445	0.50	0.024	3.750	0.517	86.150	12.585	19.350	2.425
#20	592	171.5	88	4.5	151.25	2.688	0.20	0.000	0.018	0.002	95.200	16.750	14.000	1.465
#21	534	54.0	700	10.3	12.55	8.095	0.15	0.001	0.062	0.001	28.700	8.435	12.850	2.030
#22	475	118.7	22	3.5	64.5	1.033	0.17	0.000	0.018	0.001	55.033	13.533	6.120	0.908
#23	10,145	76.0	385	4.7	18.3	2.535	0.20	0.000	0.013	0.001	30.400	11.400	7.775	0.764
#24	816	334.5	5	26.7	157	0.060	0.58	0.050	4.050	0.094	151.250	18.600	34.250	2.518
#25	16,728	97.5	3	14,450.0	1690	0.060	0.25	0.017	3.300	1.545	289.500	833.500	6435.000	230.500
#26	571	169.5	5,500	50.5	61.5	0.005	0.70	0.001	3.025	0.604	89.000	17.250	29.750	5.305
#27	515	145.7	33	2.4	100.2	0.650	0.13	0.000	0.196	0.004	63.467	17.533	6.527	0.944
#28	32,787	202.4	8	16,402.5	2104.425	0.036	0.37	0.024	0.351	0.077	260.325	891.500	6982.500	279.900
#29	660	158.5	75	38.8	118	0.025	0.50	0.009	4.135	0.550	117.000	19.850	33.350	4.400
#30	571	107.0	250	5.5	102.3	1.090	0.30	0.005	0.110	0.001	80.150	13.900	12.350	1.920
#31	436	201.7	8	6.4	32	4.700	0.40	0.000	0.063	0.004	66.800	23.667	11.033	1.423
#32	400	261.1	2930	7.9	6.533	0.083	0.23	0.022	11.530	0.586	64.782	9.186	12.797	2.154
#33	500	124.3	60	3.4	33.133	1.777	0.20	0.000	0.068	0.002	45.200	15.300	6.613	0.960
#34	281	38.2	90	6.2	14.15	6.600	0.08	0.000	0.107	0.001	19.550	6.960	7.715	1.373
#35	606	195.2	83	3.9	138.8	2.282	0.36	0.000	0.135	0.003	94.160	17.940	10.448	1.630

Table A1. *Cont.*

Wells	E.C. (μ S/cm)	HCO_3^- (mg/L)	E. Coli (CFU/100mL)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^--N (mg/L)	TOC (mg/L)	As (mg/L)	Fe^{3+} (mg/L)	Mn^{2+} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)
#36	591	101.0	8	4.8	60.35	4.600	0.15	0.000	0.041	0.001	64.100	14.900	8.200	1.130
#37	10,333	114.5	10	4.5	121.5	6.335	0.25	0.000	0.032	0.001	89.550	16.800	8.360	1.850
#38	724	237.6	5	8.8	120.4	0.790	0.30	0.007	1.219	0.284	141.200	25.700	27.200	3.140
#39	669	80.0	650	3.4	32.85	3.230	0.20	0.002	2.045	2.567	38.850	8.115	14.500	1.013
#40	592	290.0	120	26.3	2.2	0.030	3.35	0.291	0.646	0.029	20.200	27.900	78.250	45.000
#41	637	102.0	28	4.4	32.1	7.135	0.20	0.000	0.143	0.009	52.850	15.750	9.120	1.225
#42	587	211.2	90	4.2	127.86	1.292	0.18	0.000	0.034	0.002	92.220	18.460	14.480	1.980
#43	502	118.5	50	7.2	93.85	0.860	0.15	0.001	1.940	0.100	74.350	13.150	14.650	1.715
#44	251	113.0	355	1.9	19.4	0.185	0.50	0.011	2.230	0.498	20.050	7.160	43.850	1.169
#45	369	127.7	100	3.9	1.6	0.005	0.35	0.001	0.325	0.239	42.150	4.855	30.350	1.570
#46	520	169.5	175	8.4	47.05	9.380	0.20	0.000	0.481	0.013	103.700	18.300	8.570	1.840

Table A2. Data matrix for area percentages for 9 different land use categories.

Wells	Rice Field,%	Dryland, %	Fruit Farm,%	Uncultivated Land,%	Aquaculture, %	Livestock, %	Forest, %	Water Conservation, %	Human Settlement, %
#1	17	12	22	0	3	10	0	2	14
#2	1	6	1	0	0	0	25	0	44
#3	0	62	0	0	0	2	12	0	27
#4	0	0	32	5	0	0	0	4	45
#5	0	2	22	0	0	0	1	2	4
#6	0	2	2	0	52	0	0	22	8
#7	1	4	66	0	6	4	0	6	8
#8	5	17	0	0	63	0	0	1	13
#9	20	3	20	0	2	0	0	18	3
#10	0	56	4	0	0	0	0	1	36
#11	23	7	11	0	19	16	0	8	8
#12	23	11	11	0	19	15	0	8	8
#13	15	4	38	0	9	4	0	0	27
#14	0	0	64	0	0	0	5	3	25
#15	0	1	4	0	0	0	1	5	68
#16	0	1	89	1	0	1	0	0	5
#17	0	0	5	0	7	0	0	71	1

Table A2. *Cont.*

Wells	Rice Field,%	Dryland, %	Fruit Farm,%	Uncultivated Land,%	Aquaculture, %	Livestock, %	Forest, %	Water Conservation, %	Human Settlement, %
#18	3	52	9	0	1	0	0	0	33
#19	41	12	11	0	3	4	0	1	25
#20	0	12	35	0	15	0	16	9	5
#21	0	2	1	0	0	0	7	3	1
#22	0	0	98	0	0	0	0	0	2
#23	0	0	0	0	0	0	18	0	73
#24	0	0	0	0	0	0	0	31	59
#25	0	0	0	0	0	0	0	77	0
#26	0	6	8	0	9	3	0	0	62
#27	0	18	59	0	0	0	0	0	4
#28	0	0	4	0	2	0	0	8	6
#29	8	34	9	4	2	2	0	0	40
#30	0	10	30	0	20	4	4	36	4
#31	0	60	0	0	0	0	1	0	37
#32	0	0	55	0	0	0	3	0	40
#33	0	0	99	0	0	0	0	0	0
#34	0	3	77	0	3	3	0	0	1
#35	5	21	48	0	0	0	0	2	24
#36	3	9	21	2	9	9	12	3	23
#37	1	3	74	4	0	7	1	0	7
#38	1	34	19	1	25	4	1	0	8
#39	0	1	64	1	0	5	0	5	23
#40	6	14	9	0	20	0	0	3	5
#41	1	3	84	0	3	1	0	0	4
#42	34	17	23	1	12	0	0	3	2
#43	0	9	6	3	0	0	0	1	79
#44	0	0	91	2	0	1	1	0	4
#45	0	44	14	0	0	0	12	0	14
#46	0	15	52	0	3	15	0	0	10

Table A3. Data matrix for thickness for 4 different material types of unsaturated soil.

Wells	Types of Unsaturated Soil				
	Depth (m)	Gravel,%	Coarse Sand,%	Fine Sand,%	Clay,%
#1	39.2	4	9	4	0
#2	63.0	0	0	3	15
#3	39.2	0	3	1	4
#4	27.3	18	3	0	23
#5	24.0	18	0	1	0
#6	24.5	0	0	1	1
#7	36.2	0	7	3	7
#8	30.9	0	0	6	6
#9	55.6	0	0	3	0
#10	36.5	0	0	4	5
#11	29.4	0	1	2	2
#12	47.5	0	2	0	0
#13	33.8	0	5	1	5
#14	42.1	5	16	3	0
#15	53.0	0	7	3	6
#16	47.3	25	4	4	0
#17	35.8	3	3	0	0
#18	44.0	0	3	0	2
#19	38.2	0	5	5	0
#20	114.2	17	34	0	1
#21	35.5	22	0	7	0
#22	71.5	44	0	0	0
#23	66.9	13	0	8	15
#24	49.4	0	1	3	6
#25	25.3	3	0	0	0
#26	24.0	0	0	0	16
#27	78.3	59	12	3	1
#28	26.0	0	0	3	0
#29	27.0	3	5	0	0
#30	71.9	0	23	1	15
#31	62.0	31	0	0	0
#32	116.4	13	0	14	0
#33	70.5	45	0	0	0
#34	108.9	63	0	0	4
#35	75.8	65	0	0	0
#36	112.0	30	4	1	1
#37	100.0	44	0	0	0
#38	111.6	20	10	4	1
#39	149.5	3	10	2	8
#40	66.5	0	0	0	3
#41	95.8	9	4	0	16
#42	126.1	45	7	0	2
#43	117.8	9	5	12	13
#44	51.8	2	8	5	11
#45	242.1	14	4	0	0
#46	77.7	37	0	0	0

Table A4. Matrix of correlation coefficients for all variables.

	EC	HCO_3^-	E. Coli	Cl^-	SO_4^{2-}	NO_3^--N	TOC	As	Fe^{3+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Rice field	Dry-Land	Fruit Farm	Uncultivated Land	Aqua-Culture	Live-Stock	Forest	Water Conservation	Human Settlement	Gravel	Coarse Sand	Fine Sand	Clay
EC	1.00	0.09	−0.10	**0.91**	**0.91**	−0.16	−0.08	−0.03	−0.05	0.18	**0.75**	**0.91**	**0.92**	**0.92**	−0.16	−0.22	−0.24	−0.04	0.31	−0.15	−0.06	0.26	−0.13	−0.15	−0.22	−0.01	−0.13
HCO_3^-		1.00	0.02	0.09	0.11	−0.43	0.42	0.41	0.26	0.11	0.43	0.09	0.08	0.13	0.25	0.24	−0.39	−0.16	0.21	−0.03	−0.17	0.03	0.11	−0.30	−0.07	−0.05	−0.17
E. Coli			1.00	−0.08	−0.09	0.01	0.01	−0.06	−0.01	0.02	−0.06	−0.09	−0.08	−0.09	0.12	−0.14	0.01	−0.11	0.02	0.06	−0.08	−0.12	0.22	−0.17	−0.04	0.05	0.15
Cl^-				1.00	**0.99**	−0.20	−0.07	0.00	−0.04	0.26	0.83	**0.99**	**0.99**	**0.99**	−0.13	−0.17	−0.25	−0.12	0.24	−0.15	−0.13	0.43	−0.19	−0.20	−0.17	−0.08	−0.17
SO_4^{2-}					1.00	−0.21	−0.09	−0.02	−0.06	0.23	0.86	**0.99**	**0.99**	**0.98**	−0.10	−0.18	−0.24	−0.09	0.24	−0.15	−0.14	0.42	−0.19	−0.18	−0.13	−0.08	−0.17
NO_3^--N						1.00	−0.30	−0.26	−0.16	−0.25	−0.27	−0.20	−0.20	−0.21	−0.15	−0.12	0.38	0.10	−0.19	0.29	0.04	−0.23	−0.18	0.44	0.01	−0.13	−0.04
TOC							1.00	**0.92**	0.10	0.02	−0.10	−0.06	−0.07	0.02	0.14	0.14	−0.29	−0.07	0.28	−0.03	−0.10	−0.04	−0.02	−0.33	−0.17	−0.13	0.03
As								1.00	0.01	−0.08	−0.06	0.00	0.00	0.07	0.14	0.03	−0.22	−0.14	0.15	−0.05	−0.14	0.10	−0.11	−0.27	−0.16	−0.11	−0.12
Fe^{3+}									1.00	0.59	0.00	−0.03	−0.04	−0.02	−0.06	0.44	−0.17	−0.07	−0.07	−0.04	0.21	−0.06	0.07	−0.16	−0.05	0.00	−0.02
Mn^{2+}										1.00	0.25	0.28	0.27	0.27	−0.03	0.13	−0.19	−0.04	0.06	0.05	0.14	0.16	0.08	−0.38	−0.06	0.01	0.09
Ca^{2+}											1.00	**0.84**	**0.83**	**0.82**	0.05	−0.09	−0.36	−0.04	0.28	0.01	−0.23	0.49	−0.13	−0.23	−0.08	−0.15	−0.21
Mg^{2+}												1.00	**0.99**	**0.99**	−0.12	−0.17	−0.25	−0.11	0.27	−0.15	−0.12	0.44	−0.19	−0.20	−0.17	−0.08	−0.17
Na^+													1.00	**0.99**	−0.12	−0.18	−0.24	−0.11	0.27	−0.15	−0.13	0.43	−0.19	−0.20	−0.17	−0.07	−0.16
K^+														1.00	−0.12	−0.17	−0.26	−0.11	0.30	−0.14	−0.13	0.40	−0.20	−0.22	−0.18	−0.09	−0.15
Rice field															1.00	0.00	−0.19	−0.08	0.14	0.37	−0.20	−0.08	−0.14	−0.11	−0.02	−0.02	−0.22
Dryland																1.00	−0.35	−0.07	−0.01	−0.05	0.09	−0.24	0.12	−0.01	−0.01	−0.18	−0.20
Fruit farm																	1.00	0.15	−0.26	0.04	−0.22	−0.27	−0.39	0.51	0.16	−0.09	−0.02
Uncultivated land																		1.00	−0.15	0.04	−0.09	−0.15	0.20	0.13	−0.01	−0.01	0.28
Aquaculture																			1.00	0.12	−0.11	0.08	−0.23	−0.22	0.07	−0.03	−0.02
Livestock																				1.00	−0.11	−0.09	−0.17	−0.03	0.00	−0.16	−0.14
Forest																					1.00	−0.12	0.22	−0.07	0.22	0.11	0.20
Water conservation																						1.00	−0.21	−0.26	0.05	−0.18	−0.08
Human Settlement																							1.00	−0.26	−0.13	0.39	0.50
Gravel																								1.00	−0.07	−0.21	−0.26
Coarse sand																									1.00	−0.06	0.06
Fine sand																										1.00	0.14
Clay																											1.00

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