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Cause Analysis of Water Quality Variability of Drinking Water Reservoirs by Parameter Optimization and Pattern Recognition

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Abstract: The increasingly serious river water pollution poses great threat to the drinking water security in Zhejiang Province, China. Reservoirs therefore played an increasingly important role as the drinking water source in recent years. An investigation on the drinking water reservoirs in Zhejiang Province was conducted to better understand the causes for variability of water quality. 73 drinking water reservoirs were selected as the subject investigated, and 20 environmental parameters possibly affecting water quality were extracted both at 1000m buffer and watershed scale for cause analysis. Integrated CfsSubsetEval and Scatter search method (Cfs-Ss) were employed for parameter reduction and optimization followed by support vector machine (SVM) to simulate reservoir water quality using the optimal subsets of parameters. According to the parameter optimization result, industrial emission is the most important factor influencing the water quality of reservoirs. Land use and human habitation also impact water quality level. The water quality classes predicted by SVM models constructed by optimal subsets of parameters from buffer, watershed and both of them had accuracy of 71.43%, 66.67% and 80.95% respectively in attribution to the right classes. The results in this study offers insight into the factors impacting water quality of reservoirs and can help planners and managers to better regulate and protect the reservoir water resources.
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Keywords: Drinking water; Reservoir; Water quality; Parameter optimization; Pattern recognition

1. Introduction

The water of rivers have been seriously deteriorated in Zhejiang Province in the past years, and the exacerbation has been increasingly severe recently, mainly due the increasing pollution and poor management. Reservoir, as the quality source of drinking water, has been playing increasingly important role in Zhejiang Province. By 2010 the number of reservoirs employed as drinking water sources account for 51% of the total number of centralized drinking water sources in rural areas and 69% in urban areas (Yu et al., 2007). Drinking water derived from about 500 reservoirs has been supporting about 70% of the population in Zhejiang Province (He et al., 2011). Therefore, maintaining good water quality of these reservoirs is particularly important for both water security and economic development locally and nationally (Jiang, 2009). According to the monitoring data, the overall status of the water quality of drinking water source reservoirs is favorable in Zhejiang, but a number of them have been undergoing increasing pressures and degradations in the past years and there is a trend of deterioration recently (Lv et al., 2010). With the development of economy and urban construction, sewage discharges rapidly increased, which severely damaged the reservoir environment, seriously affecting the function of reservoirs. At the same time, with the improvement of living standards, people's demand for the quality and quantity of water is becoming much higher (Yu et al., 2007). Therefore, it is urgent and significant to better understand the status of the water quality of drinking water reservoirs and the factors which impact the water quality.

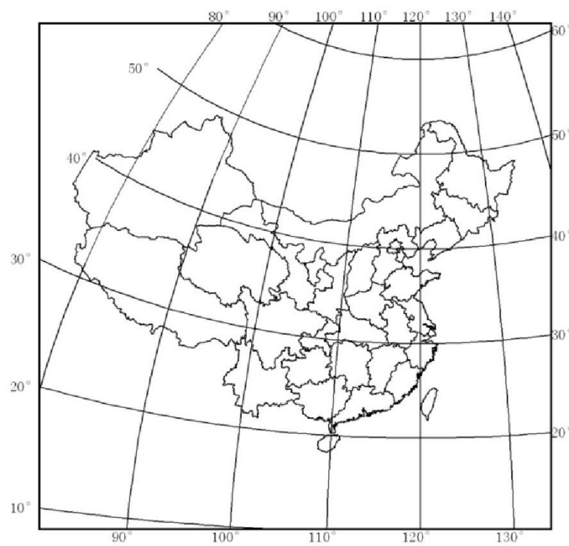
Nevertheless, it is a big challenge to identify the causes of water quality variability due to the limitation of the availability of data and to the absence of a unified theoretical and methodological system, especially for objects with great numbers or on a large scale. Most of the previous researches referred to a single or a small number of reservoirs (Yang et al., 2009; Weng et al., 2009; Zou, 2012), thus lack generalizability and potential replication. Based on the support of sufficient data and effective technologies, we took 73 drinking water source reservoirs as the subject investigated, trying to construct a methodological system for analysis of the causes of water quality variability of reservoirs. 20 environmental parameters representing anthropogenic activities, attribute of reservoirs and climate that possibly affecting water quality were extracted both at 1000m buffer and watershed scale for cause analysis. In order to figure out the parameters that are most related to the water quality, we chose CfsSubsetEval and Scattersearch method (Cfs-SS) for parameter reduction and optimization to find out groups of parameters that could recognize the water quality of reservoirs best. Multivariate analysis has been most widely used in the studies of water quality of water bodies (Reynoldson et al., 1997; Singh et al., 2004) However, the relationships between water quality of reservoirs and environmental factors are generally non-parametric and implicate complex interactions. Therefore, statistical methods would be difficult to get favourable model fits (Cheng et al., 2009). Support vector machine (SVM) is a method of pattern recognition based on statistical learning theory and has great advantages of resolving small sample, nonlinear or high dimensional matters. It has been widely used in various fields (Schuldt et al., 2004; Chen et al., 2001; Foody et al., 2006), but is seldom applied for studies of water quality. In this study, SVM was employed to classify the water quality levels of reservoirs. In addition, the remote sensing and GIS technologies have developed fast in recent years and have been successfully applied in various research fields. By contributing to multi-information retrieval and comprehensive multi-level analysis, remote sensing and GIS technologies have become powerful tools for ecological environmental investigations, especially on the issues with wide spatial scales (Krivtsov, 2004; MacMillan et al., 2004). In this study, we applied RS for deriving of land-use parameters from remotely sensed TM images. GIS techniques was used for organization of all data.

Given the current situation of Zhejiang Province and the advantages of adopted method, this paper has four main objectives: 1) to analyse the spatial distribution of water quality of drinking water reservoirs in Zhejiang Province; 2) to develop a method integrating GIS, remote sensing, Cfs-SS and SVM for analysis of causes impacting water quality of reservoirs at both buffer and watershed scale. 3) to identify the parameters that most closely relate to the water quality of reservoirs and to evaluate the ability of subset of parameters for predicting the water quality classes; 4) to analyse the relationships between important parameters and water quality of reservoirs and to provide useful reference for policy makers to promote the protection of reservoir water resources.

2. Material and Methods

2.1. Study area

Zhejiang Province, which is located in China's eastern coastal area, is one of the most developed provinces in China. With an area of 101800 Km^2 and a population of 54.77 million, Zhejiang is one of the smallest and most densely populated provinces. The terrain in Zhejiang is complex and is given priority to mountains and hills, accounting for 70.4% of the area of the province. Plains and basins cover 23.2% and rivers and lakes are 6.4%. Characterized by subtropical monsoon climate, the region is warm and humid with plenty of rainfall, distinct seasons and sufficient sunshine. The annual average temperature ranges from 15 ℃ to 18 ℃ and the annual average precipitation is between 980 to 2000 mm. There are 479 reservoirs serving as sources of drinking water in Zhejiang Province by 2010. We selected 73 of them as subject investigated, which are of the most important drinking water source reservoirs and can basically represent the overall status in Zhejiang Province. Their locations and relative sizes were showed in Figure 1.



2.2. Data

The data used is listed as follows: 1) remote sensing data, including 9 TM images obtained in year 2010, 2) DEM (30 m), administrative division, drainage map, supplied by the environmental science research institute, Zhejiang Province, 3) reservoir water quality record and socio-eonomic data, provided by the environmental science research institute, Zhejiang Province, 4) meteorological records, obtained from the China Meteorological Data Sharing Service System.

Source data was further processed with the following steps: 1) to delineate the boundaries of watersheds using DEM in the Hydrology module of ArcGIS 9.3, assisted by the drainage map (Figure 2),

2) to delineate the boundaries of 1000m buffer using Buffer Analysis in ArcGIS 9.3; 3) to classify the land cover into water bodies, forest, arable land, construction land, road and unused land using object-oriented classification method integrated with visual interpretation in eCognition 8.7 software. The results were validated with high resolution images as well as field investigation for some regions. The accuracy of classification was 85.2% (Kappa = 0.81), meeting the requirements for further usage. 4) interpolation of meteorological data with the kriging method, 5) to unify the geo-reference of all layers with Universal Transverse Mercartor (UTM) grid system, WGS_1984 geodetic datum, 6) to overlay the watershed boundary map and buffer area map on all the other layers to compute parameters in the watersheds as well as in the 1000m buffers using ArcGIS.

3. Methodology

3.1. Framework of the method

The framework of the approach in this study was divided into several steps. The spatial distribution of water quality were firstly analysed. Integrated CfsSubsetEval and Scattersearch method (Cfs-Ss) were employed for parameter reduction and optimization followed by support vector machine (SVM) to simulate reservoir water quality using the optimal subsets of parameters. The total 73 reservoirs were randomly divided into two groups, 52 for training and 21 for testing.

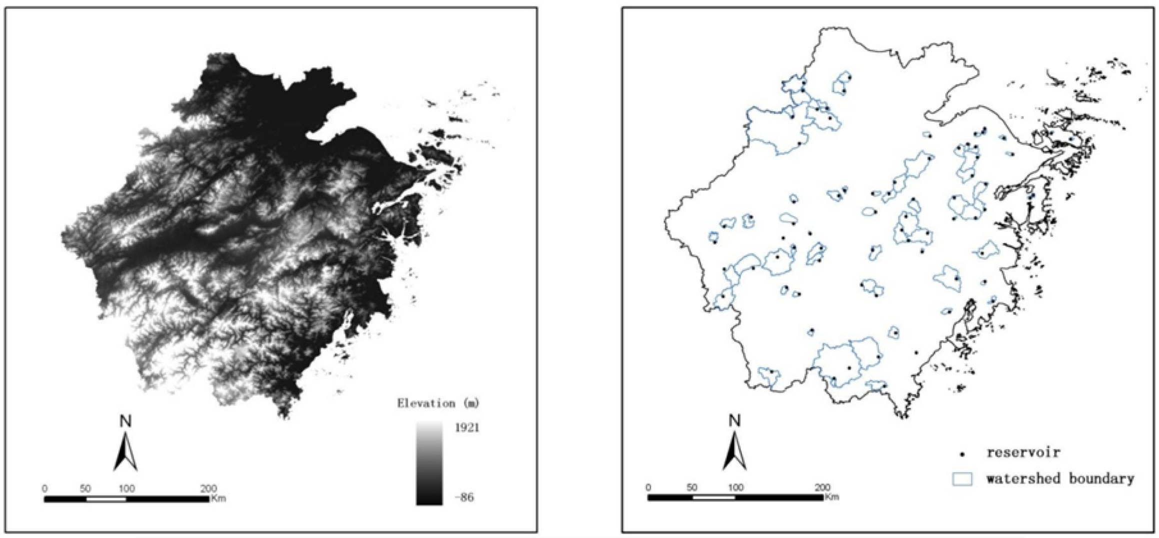


Figure 1. Locations and Relative Sizes of Sampled Reservoirs in Zhejiang Province

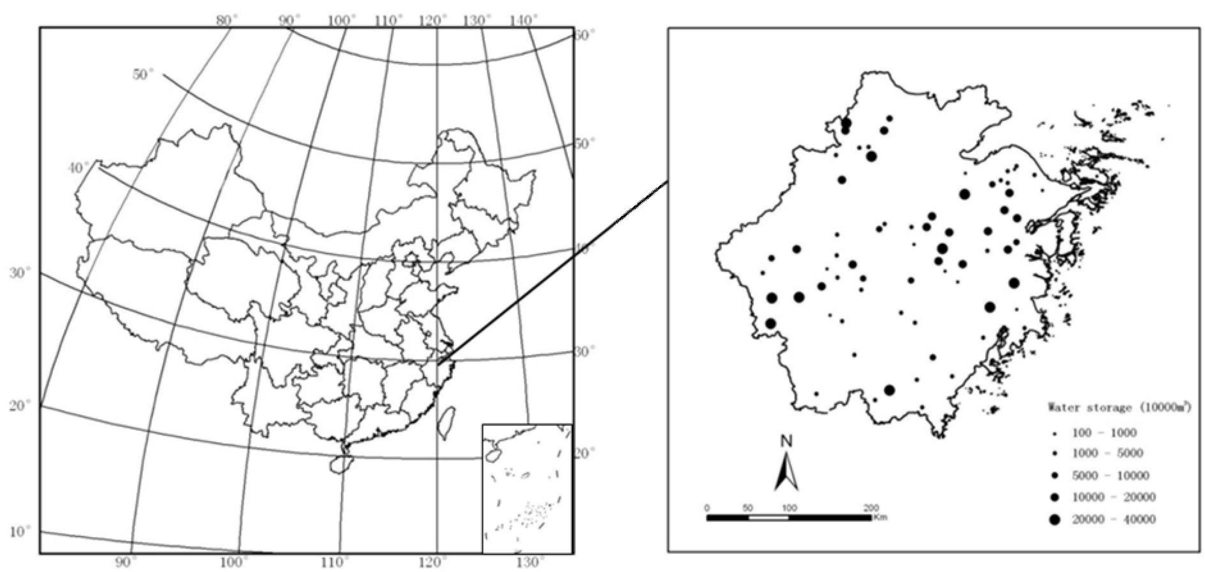


Figure 2. (a) The DEM of Zhejaing Province; (b) The Boundaries of Watersheds of Sampled Reservoirs

3.2. Reservoir water quality classes

By following the national quality standards for surface waters in China (GB3838-2002), the reservoir water quality were assessed using single factor evaluation method with 27 water-quality indices. The water quality classes used for SVM process in this study were established with the monthly mean values of all the indices in year 2010. All the 73 reservoirs reached the first (14 reservoirs), second (47 reservoirs) and third (12 reservoirs) level of the surface water quality standard, meeting the demand for drinking water source.

3.3. Collection of the parameters

By comprehensively considering the regional characteristics of Zhejiang Province, as well as the availability, comparability and reliability of the data, 20 parameters representing anthropogenic activities, attribute of reservoirs and climate were selected as the independent variables (Table 1).

Table 1. Name and Abbreviation of Parameters

Name	Abbreviation
Percentage of forest	Forest%
Percentage of farmland	Farmland%
Percentage of construction land	Construction%
Degree of fragmentation	DOF
Population density	Pop_D
Gross domestic product per unit area	GDP
Industrial output value per unit area	Ind_output
Industrial wastewater discharge per unit area	Ind_wastewater
Industrial water consumption per unit area	Ind_con
Chemical oxygen demand discharge per unit area	COD
Ammonia nitrogen discharge per unit area	NH_4-N
Petroleum discharge per unit area	Petroleum
Industrial solid wastes discharge per unit area	Ind_solid
Domestic sewage discharge per unit area	Dom_sewage
Sewage treatment rate	Treatment%
Distance to city	Distance
Elevation	
Storage capacity	Capacity
Age	
Precipitation	

Socio-economic parameters

Many studies have reported that the human habitation and economic activities have great influence on the water quality in adjacent aquatic systems (Su et al., 2011; Falkenmark and Widstrand, 1992), because the anthropogenic activities and development of economy cause emissions of domestic sewage and industrial waste, which threat the health of water environment. Based on the procurability of data, we selected Res_D, Exo_D, GDP, Ind_output, Ind_wastewater, Ind_con, COD, NH_4-N, Petroleum, Ind_solid, Dom_sewage, Treatment% as independent variables in our study. The statistical data were all of year 2010, and at the administrative scale. Considering the close connection between them to construction land use, we calculated the corresponding amount for each buffer and watershed according to the proportion of construction land in the 1000m buffer and watershed to that in the administrative region, and then used the area of watershed to calculate the population density and per unit area of the other variables.

Land use

It is demonstrated by many investigations that land uses have significant impacts on the adjacent hydrologic systems (Lenat and Crawford, 1994; Bolstad and Swank, 1997; Liu et al., 2000; Tong and Chen, 2002). The patterns of land use are closely linked to the characteristics of anthropogenic activities, which in turn influence the processes the pollutive substances carried into aquatic systems. Water quality in various aquatic systems has been found to be closely related to the compositions of land use types or spatial configurations of land use patterns within watershed (Lenat and Crawford, 1994; Tong and Chen, 2002). In this study, four parameters were employed to represent the land use: percentage of forest, percentage of farmland, percentage of construction land and degree of fragmentation.

The degree of fragmentation can reflect the status of the integrity of terrestrial ecosystem and the conditions of landscape pattern, and is computed as follows:

$$C_i = N_i/A_i \quad (1)$$

where Ci is the degree of fragmentation; Ni is the sum of patches; Ai is the regional total area.

Geographical features

Geographical position reflect the transport processes for pollutants across the landscape, and is closely related with the local land use patterns as well as the economic development, and then has significant impact on the water quality of reservoirs. We chose elevation to indicate the geographical position of reservoirs.

The effect of city on water quality had been widely discussed (Pesce and Wunderlin, 2000; Alberto et al., 2001). In this study, the distance from reservoir to city was extracted to assess the influence of city on reservoir water quality.

Capacity and age

Reservoirs with different storage capacities have unlike purification abilities and reservoirs with different ages endure inequable risks, which both will lead to water quality differentia. In order to explore the relationship between the storage capacity as well as age and the reservoir water quality, we prepared them for modeling.

Precipitation

Drought and uneven distribution of precipitation caused by climate change will greatly reduce the runoff and decrease the storage of reservoirs, while heavy rains will impact the ecological environment and vegetation growth, and can further increase the risks of soil erosion and deterioration of water quality. The precipitations for each watershed were obtained through the Kriging interpolation method based on the records from 18 monitoring points in Zhejiang Province in 2010.

3.4. Parameter reduction and optimization

After the parameters have been discretized by Entropy/MDL method, the CfsSubsetEval-Scattersearch (Cfs-Ss) method was adopted to perform reduction and optimization. Cfs (correlation-based feature selector) is a filtering algorithm for feature selection using heuristic evaluation function, Merit, which is based on the correlations between parameters (Hall, 1999). CfsSubsetEval is a subset evaluation method based on Cfs (Vasconcelos et al., 2005). The values of Merit were used for subset selection. The features which are relatively useless for prediction as well as highly relevant to others would be discarded. Scattersearch (Ss) is a heuristic search method for better solution based on the CfsSubsetEval. The detailed knowledge of Ss could be found in (Herrera, 2006; Glover et al., 2000). The Cfs-Ss process was operated in Weka 3.6 software.

$$\mathrm{Merit} = \frac{k\bar{r}_{cf}}{\sqrt{k+k(k-1)\bar{r}_{ff}}} \quad (2)$$

Where k is the numbers of the parameters in the subset; $\bar{r}_{cf}$ is the average correlation coefficient between parameters and classes; $\bar{r}_{ff}$ is the average correlation coefficient between parameters.

4. Result and discussion

4.1. Spatial distribution of reservoir water quality

The spatial distribution was analysed in GIS as was shown in Figure 3. Most of the reservoirs with best water quality located at the southwest mountainous areas, and few were at northwest and central regions. The reservoirs with relatively poor water quality dispersedly distributed at the north, northeast and southeast areas. We can see from Figure 3, the reservoir water quality varied from southwest to northeast with a trend of degradation.

The distribution of reservoir water quality is consistent with that of terrain in Zhejiang which is ladder-like distributed, tilting from southwest to northeast. It is mainly covered by mountain land in the southwest and hilly area in the central region and alluvial plain in the northeast. The landforms influences on reservoirs in various ways. Firstly, landform affects the surface runoff process, and thus relates to the transfer of sanitary sewage and industrial pollutants (Tim and Jolly, 1994). Secondly, the land use, in a manner, is determined by landforms (López et al., 2001). For instance, the mountainous regions are often dominated by forest land with less construction land or arable land, while plain and hilly areas have more construction land and agricultural land comparatively. Different land use styles have inequable influence on regional water body, leading to indirect association between topography and water quality. Furthermore, the local economy is affected by landforms (Caldas et al., 2007). For example, due to the inconvenience of traffic, the mountain area is economically backward relatively, hence much less contaminants would be issued than other places. Meanwhile, with the minor population density and lower living standard, these regions produce less sanitary sewage.

4.2. Parameter optimization using Cfs-Ss method

The spatial scale effect plays a vital role in studying about the influencing variables of water quality of reservoirs due to the distinctive hydrologic and biogeochemical processes in different spatial scales. Up to now no widely accepted conclusion has been reached that which scale is best for analyzing determinants of reservoir water quality. In this study we calculated environmental parameters from both 1000m buffer and watershed to better understand the determinants in different scales.

The selection result of first six optimal subsets was shown in Table 2, these parameters primarily represented the surrounding anthropogenic activities including economic activities, human habitation and land use. They were most closely related to the water quality of study reservoirs. The rest of the parameters were excluded from the optimal subsets might not because they have no relation with the water quality of reservoirs, but because they do not significantly affect the water quality compared with the parameters listed in Table 3 or they are highly relevant to these parameters. It indicated that the causes for reservoir water quality variability were very complicated and comprehensive.

The result showed that the influence of factors on water quality level changed with scale. The Ind_wastewater and Dom_sewage were the most important factors at both buffer and watershed scale, while the land use parameter Construction% played more significant role at buffer scale. The Merit values of subsets from two scales were higher than that from a single scale, indicating that combining variables from different spatial scales might be a better way to predict the water quality classes.

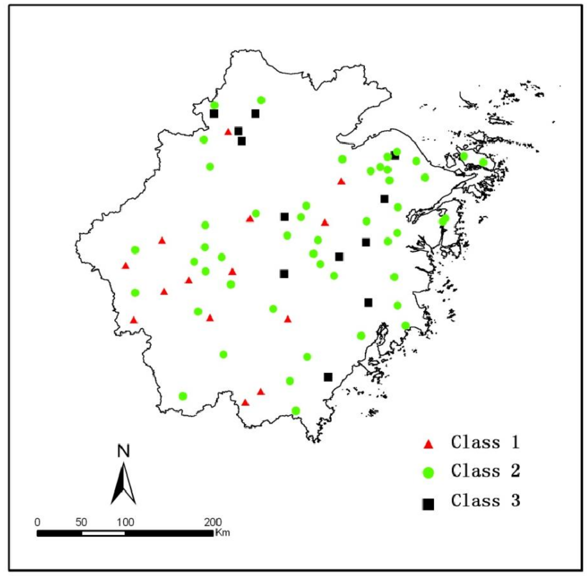


Figure 3. The Spatial Distribution of Reservoir Water Quality

Table 2. Parameter Selection Result

1000m buffer scale*	Merit	Watershed scale	Merit	1000m buffer and watershed	Merit
Ind_wastewater*, Dom_sewage*, Construction%*	0.7409	Ind_wastewater, Dom_sewage	0.7366	Ind_wastewater, Dom_sewage, Construction%*	0.7512
Ind_wastewater*, Construction%*, Pop_D*, Ind_output*, Petroleum*, Forest%*	0.7142	Ind_wastewater, Pop_D, Ind_output	0.7024	Ind_wastewater, Dom_sewage, Pop_D*, Ind_output, Construction%*	0.7239
Ind_wastewater*, Dom_sewage*	0.6076	Ind_wastewater, Dom_sewage, Petroleum, Construction%, GDP	0.6417	Ind_wastewater, Pop_D, Forest%*, Construction%*, GDP	0.7022
GDP*, Ind_output*, COD*, NH4-N*, Ind_solid*, Dom_sewage*	0.5562	Ind_wastewater, Ind_output, Construction%, Distance, Ind_solid, Forest%	0.5902	Pop_D, Ind_solid*, Dom_sewage*, NH4-N, Petroleum, Construction%	0.6571
Pop_D*, Petroleum*, Ind_solid*, Ind_output*, Distance*, **Ind_con***	0.5154	Pop_D, Construction%, Dom_sewage, GDP, Ind_solid, Petroleum, NH4-N	0.559	Ind_wastewater*, Dom_sewage, GDP*, Ind_output, Distance, Ind_con, Petroleum*	0.5968
GDP*, NH4-N*, COD*, Pop_D*	0.4356	Ind_con, Dom_sewage, Pop_D, Distance	0.4836	Ind_wastewater*, Dom_sewage*, GDP*, COD*, GDP, Dom_sewage,	0.5523

4.3. Pattern recognition and accuracy evaluation

Based on the parameter optimization result, subsets (Ind_wastewater*, Dom_sewage*, Construction%*), (Ind_wastewater, Dom_sewage) and (Ind_wastewater, Dom_sewage, Construction%*) were employed as the independent variables, and SVM was used to simulate reservoir water quality classes. The training and testing processes regarding SVM were accomplished in the Lib - SVM platform. C – SVC method was chosen for classification, using radial basis kernel function as the kernel function. The penalty factor c and optimal parameter γ used in SVM were computed by grid. py provided by Lib – SVM. The 52 training reservoirs were randomly selected from the range of water quality classes, including 10, 34 and 8 reservoirs from the C1, C2, and C3 classes respectively. They were employed to build models, and the testing group was then used to assess the predictive ability of constructed models. As was shown in Table 3, the overall accuracy of the three models in rightly attributing reservoirs to their respective water quality classes were 71.43%, 66.67% and 80.95%, respectively. It is indicated that optimal subset from 1000m buffer could somewhat better predicts the water quality classes than that from the watershed scale, and variations of water quality were most correctly predicted by the combined parameters.

Table 3. Recognition Accuracy

Scale	Variables	Accuracy
Buffer	Ind_wastewater*, Dom_sewage*, Construction%*	71.43%
Watershed	Ind_wastewater, Dom_sewage	66.67%
Buffer and watershed	Ind_wastewater, Dom_sewage, Construction%*	80.95%

4.4. Major problems related to reservoir water quality in Zhejiang Province

Economic development and industrial pollution

The developmental pattern in Zhejiang Province was characterized by high input, high consumption, low technological and low efficient in the past, after years of blind pursuit of rapid economic development, the ecological environment in Zhejiang has been seriously polluted. Unfortunately, the terrible situation is continuing. By referring to the statistics data, during 2006 to 2010, the wastewater emissions showed a trend of increase year by year, and the average annual growth rate of industrial wastewater and domestic sewage emissions were 2.5% and 8%, respectively. Based on the statistics in 2010, for every $100 million of GDP, 0.88 million tons of waste water were discharged, and for every $100 million of industrial output value, there produced 0.88 billion m^3 of industrial waste gas and 18.4 thousand tons of industrial solid waste, which were several times or even dozens of times higher than that in developed countries.

Population density and water quality

Living of people produces residential pollutants, mainly including food waste, washing residues, hospital sewage and household garbages (Du et al., 1999). Zhejiang Province is densely populated and the high population density in reservoir catchments has always been one of the primary challenges in reservoir water protection. With the rapid improvement of people's living standard in recent years, domestic pollutants with abundant nitrogen and phosphorus and nutrients have been greatly increased. However, due to the lack of proper processing of the pollutants, most of them were directly discharged into the natural environment and carried by runoff into the water bodies (Yu et al., 2007). Moreover, the reservoir areas are rich in tourist resources. Yet the exploration of catering industry and tourism have given rise to the incensement of fluid population and thus the raise of pollutants.

Effects of urbanization on reservoir water quality

Many studies indicate that there is a strong relationship between land use and the water quality in adjacent water bodies (Lenat and Crawford, 1994; Tong and Chen, 2002; White and Greer, 2006). Consistent with previous researches, our result showed that the construction land and forest were closely related to the water quality of adjacent water bodies. It might be explained that the expansion of construction land means the industrial development or population increasing, leading to more industrial or domestic pollutants, while forest land benefits the water conservation and pollution interruption.

Zhejiang Province is one of the most developed provinces in China and has been undergoing the rapid urbanization in the past decades. Despite of the fast economic growth, the overlook of ecological protection and absence of scientific development concept during urbanization have seriously lead to excessive consumption of resources and various environmental problems which in turn limited the further development and the daily life of people.

4.5. Conservation implications

An important goal of this study is to offer assistance to decision makers and practitioners in drinking water reservoir protection. Owing to the protective actions during the past years, the overall water quality of drinking water reservoirs is still desirable in Zhejiang Province. However, there are great pressures from anthropogenic activities on the reservoir water environment, urging us to take related measures for more strict protection and pollution abatement. The planning of residential and industrial construction and the development of tourism should involve full consideration of environmental and water protection. Discharge of domestic sewage and industrial wastewater should be strictly regulated to prevent direct pollution to water. It is also important to raise the public awareness of environmental protection as well as scientific understanding. It is not just a matter of the government, but a practical issue that is closely related to the living and health of each individual, which needs the joint efforts of the decision makers and residents.

It is worth mentioning that currently a strategy named Main Function Region Strategy is being implemented in Zhejiang Province, which is characterized by customized development policies in different zones, such as the optimization and upgrading of industry promoted in northeast plain hilly areas and southeast coastal areas and the limited development policy in southwest areas. It is significant for the reservoir water protection. Nevertheless, due to the imbalance of land resources, there was a tendency of shift of industry from southeast coastal areas to southwest sparsely populated areas, imposing more and more pressure upon the reservoirs in this area. Therefore, it is significant for drinking water source protection to properly execute the strategy and strictly regulate the development and transfer of industry.

5. Conclusions

In this study we first analysed the spatial distribution of water quality of 73 drinking water reservoirs in Zhejiang Province, to find that the water quality was spatially degraded from southwest to northeast. Then 20 environmental parameters possibly affecting water quality were extracted both at 1000m buffer and watershed scale for cause analysis. Integrated CfsSubsetEval and Scattersearch method (Cfs-SS) was employed for parameter reduction and optimization. It is determined that most of the parameters comprising the selected subsets provided by anthropogenic factors including industrial activities, human habitation and land use should be responsible for reservoir water quality variability. The support vector machine (SVM) was used to simulate reservoir water quality using the optimal subsets of parameters, and reasonable accuracy was obtained. It was shown that optimal subset from 1000m buffer could somewhat better predicts the water quality classes than that from the watershed scale, and variations of water quality were most correctly predicted by the combined parameters. The methodology proposed in this study was quick, robust and informative for identification of causes of variation of reservoir water quality and is applicable to other areas, potentially serving as an operational tool for planners and managers.

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